NASA CR–135035

TRANSMITTER EXPERIMENT PACKAGE FOR THE COMMUNICATIONS TECHNOLOGY SATELLITE

by B. Farber, D.S. Goldin, B. Marcus, and P. Mock

TRW®
DEFENSE AND SPACE SYSTEMS GROUP

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3–15839

(NASA-CR-135035) TRANSMITTER EXPERIMENT PACKAGE FOR THE COMMUNICATIONS TECHNOLOGY SATELLITE (TRW Defense and Space Systems Group) 200 p HC A09/MF A01 CSCL 17B
N77-24332
Unclas
G3/32 26074

NASA CR–135035

TRANSMITTER EXPERIMENT PACKAGE FOR THE COMMUNICATIONS TECHNOLOGY SATELLITE

by B. Farber, D.S. Goldin, B. Marcus, and P. Mock

TRW
DEFENSE AND SPACE SYSTEMS GROUP

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3–15839

1. Report No. 135035	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Transmitter Experiment Package for the Communications Technology Satellite		5. Report Date
		6. Performing Organization Code
7. Author(s) D.S. Goldin, B. Farber, P. Mock, B. Marcus		8. Performing Organization Report No 135035
		10. Work Unit No.
9. Performing Organization Name and Address TRW Defense and Space Systems Group Redondo Beach, California 90278		11. Contract or Grant No. NAS3-15839
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address NASA Lewis Research Center Cleveland, Ohio		14 Sponsoring Agency Code 6115

15. Supplementary Notes

16. Abstract

This final report describes the operating requirements, system design characteristics, high voltage packaging considerations, nonstandard components development, and test results for the Transmitter Experiment Package (TEP). The TEP is used for broadcasting power transmission from the Communications Technology Satellite. The TEP consists of a 12 GHz, 200-watt output stage tube (OST), a high voltage power processing system that converts the unregulated spacecraft solar array power to the regulated voltages required for OST operation and a variable conductance heat pipe system that is used to cool the OST body.

17. Key Words (Suggested by Author(s)) Transmitter Communications Technology Satellite Power processing system Heat pipe	18. Distribution Statement Unclassified - unlimited STAR category

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	[illegible]	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 6-71)

DOCUMENT RELEASE AUTHORIZATION

NASA Scientific and Technical Information Facility P.O Box 8757, Balt/Wash International Airport, Maryland 21240	Control No Date

DOCUMENT DESCRIPTION

TITLE Transmitter Experiment Package for the Communications Technology Satellite

AUTHOR(S): D. S. Goldin, B. Farber, P. Mock, B. Marcus

ORIGINATING ORGANIZATION TRW Systems Group Redondo Beach, CA

COGNIZANT NASA CENTER Lewis Research Center Cleveland, Ohio

CONTRACT NO NAS3-15839

SECURITY CLASSIFICATION
TITLE Unclassified DOCUMENT Unclassified

REPORT NO.

DATE

NASA CR NO 135035

NASA TMX NO

WORK UNIT NO

NASA TECHNICAL MONITOR Clifford E. Siegert

OFFICE CODE 6115

THE FOLLOWING TO BE COMPLETED BY THE RESPONSIBLE NASA PROGRAM OFFICER OR HIS DESIGNEE

(Further information is available in SP-7034 entitled R & D Reporting Guidance for Technical Monitoring of NASA Contracts)

I Document may be processed into the NASA Information System as follows

- [X] May be announced in STAR (or CSTAR if a limited availability is checked below)
- [ ] May not be announced (The attached letter may be consulted for information pertaining to the NASA non-announcement series)
- [ ] May not be entered into the System because

(Provide a brief statement to be quoted in answering requests for the referenced document)

II Document may be made available as checked below

- [X] Publicly Available
- [ ] Classified but Unlimited to Security Qualified Requesters
- [ ] U S Government Agencies and Contractors Only
- [ ] U.S Government Agencies Only
- [ ] U S Government Agencies, NASA and NASA Contractors Only
- [ ] NASA and NASA Contractors Only
- [ ] NASA Headquarters and Centers Only
- [ ] Other Limitations (Specify)

Signature (Program Officer or Designee). Clifford Siegert

Office Code: 6115

Telephone No 433-4000 EXT 6625

Date Signed 3-9-77

MAILING LABEL
Use open window envelope
or
Clip out and paste

ib

TO:

NASA Scientific and Technical
Information Facility
Attn Accessioning Department
P.O Box 8757
Balt/Wash International Airport
Maryland 21240

FF 427 FEB 75

CONTENTS

CONTENTS (Continued)

1. INTRODUCTION

The United States' prime experiment flown on the joint USA-Canadian Communications Technology Satellite (CTS) is a high power, high efficiency traveling wave tube and associated power processor designated TEP, Transmitter Experiment Package. Specifically, the TEP includes the output stage tube (OST), a power processor system (PPS), interconnecting cables between OST and PPS, and associated thermal control equipment, the latter including a variable conductance heat pipe system (VCHPS).

The OST consists of a coupled cavity 12 GHz TWT and a 10-element multistage depressed collector and is capable of producing 200 watts RF (240 peak) output at an efficiency greater than 50 percent.

The PPS consists of power conditioning circuitry used to convert solar array power (from a nominal 76 Vdc array) to the appropriate voltage and current levels required for operation of the OST. It also provides command, protection, and active thermal control functions for the TEP, and includes instrumentation and telemetry signal conditioning circuitry for monitoring TEP status.

The basic OST configuration and PPS electrical interfaces under full RF drive (saturation) conditions are illustrated in Figure 1-1. The electron beam flowing from cathode to the multistage depressed collector (MDC) interacts with an RF signal injected at the input of the coupled cavity structure, and in the resulting interaction the RF signal is amplified in the cavity region.

The multicollector design significantly improves the dc-to-RF conversion efficiency, which is especially important in high power traveling wave tube design. This is accomplished through the connection of the different collector electrodes to fixed voltages ranging between zero and cathode potential. The collector voltages are selected such that the beam electrons arriving in the collector region are sorted according to velocity and are collected at voltages appropriate for minimizing energy loss and the resultant thermal dissipation. Because the electron velocity spectrum changes with RF input drive, the beam current division between the various collectors also varies, but total beam current remains constant. Upon establishment of the electron beam, nearly all the electrons leaving the cathode surface reach the collectors with the lowest (most negative) potentials in the absence of RF drive. Very few intercept the intervening (more positive) collectors. As RF drive is increased, electrons distribute on collectors with more positive potential. Thus, a widely varying load characteristic is presented to collector output supplies over the full range of RF drive.

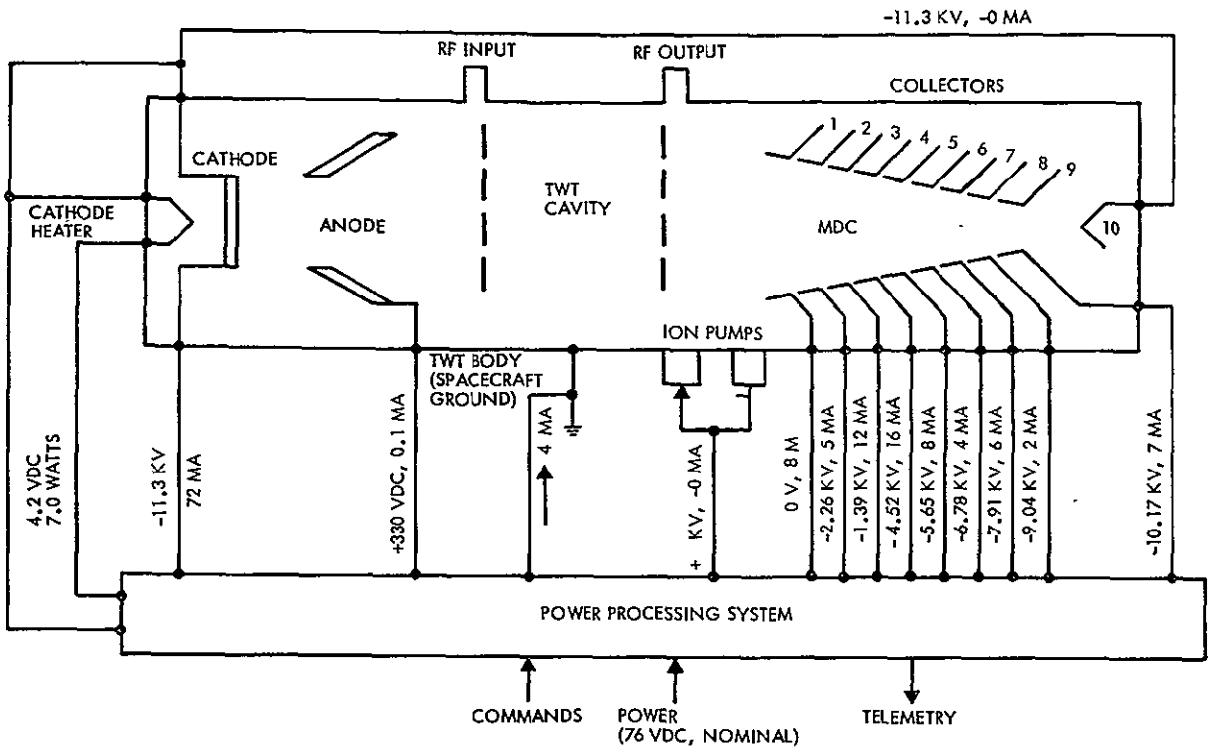


Figure 1-1. TWT Elements and PPS Interface

The major supplies and functions of the PPS are:

- Cathode/collector supply for developing a well-regulated cathode-body voltage of -11.3 k Vdc with extremely low ripple (0.01 percent peak-to-peak) and 10 MDV voltages ranging from 0 to -11.3 k Vdc
- Anode supply for developing a regulated, adjustable +150 to +550 Vdc
- Cathode heater supply
- Ion pump supply

- Command and protection logic system
- Thermal heater control system
- Telemetry signal conditioning and associated instrumentation supplies.

Total output power capability of the PPS is approximately 500 watts.

Mechanically, the TEP is configured with the PPS assembly mounted on a common baseplate with the OST. Because of the high dissipations encountered during operation in both the PPS and OST (up to 225 watts), a thermal control system was required to divert dissipation to a remote, thermally coupled radiator system. The VCHPS provides this function and is described in detail in the body of this report.

The PPS is made up of a low voltage section and an isolated high voltage section. Basic dimensions are 7 inches high, 9.5 inches wide, and 20.5 inches long. PPS weight, including the added structure to support the OST, is 29.28 pounds. Weights of the OST and VCHPS are 26.19 and 16.4 pounds, respectively, for a total system weight of 71.87 pounds.

This final report primarily contains the design and performance description of the TEP, but omits any discussion of the design and RF performance characteristics of the OST, which is covered in a separate report.*
Section 2 is a brief description of the TEP electrical implementation and performance, followed by Section 3 which outlines the TEP design requirements. In Section 4, PPS Design, system design trades are briefly described along with the implementation selected to satisfy all TEP interface requirements (OST to PPS, TEP to spacecraft). The remainder of this section details the electrical, mechanical, and thermal design of the PPS. Section 5 presents TEP performance characteristics as determined in qualification and acceptance testing, and the design and performance characteristics of the VCHPS are given in Section 6.

*NASA CR 135029

2. DESCRIPTION

The electrical implementation of the PPS portion of the TEP is illustrated in Figure 2-1. Interconnection of the various supplies and their interface with the spacecraft command and telemetry systems are indicated.

Raw power is derived from two sources. The primary bus (solar array source) supplies a minimum of 471 watts at 76 Vdc nominal to the major load — the cathode/collector supply. A limited amount of power is derived from a separate 27.5 Vdc solar array/battery source and is used to power the anode, cathode heater, and ion pump supplies, the last used to maintain vacuum conditions in the MDC assembly. The TWT cathode heater can thus be powered during eclipse, avoiding excessive thermal cycling of the heater element. The secondary source also powers various internal supplies which are used to operate the command, protection, and instrumentation systems and for generating drive power for the cathode/collector supply. Input line filters at both power inputs provide low ac source impedance for downstream switching regulators to minimize conducted interference. The power buses are then directly wired to each output supply with on/off control excercised at low levels in the control logic sections of the individual output supplies. The 76 V bus relay indicated is for fault clearing purposes only.

A thermal (substitute heater) control system is provided for maintaining equipment platform temperature to an acceptable level when the PPS is not energized. Strip heater elements are located on the PPS baseplate to accomplish this function.

The command and protection logic system primarily controls startup and shutdown of the TEP in a prescribed sequence. Twenty command signals are processed with logic arranged such that false command signals are prevented from causing undesired actions. Seven of the 20 command signals are used to control and adjust output power; three are associated with the PPS turn-on and thermal control system, five are associated with protective functions, two with instrumentation, and two are used to operate the 76 volt bus fault clearing relay and are associated with TEP failure mode operation.

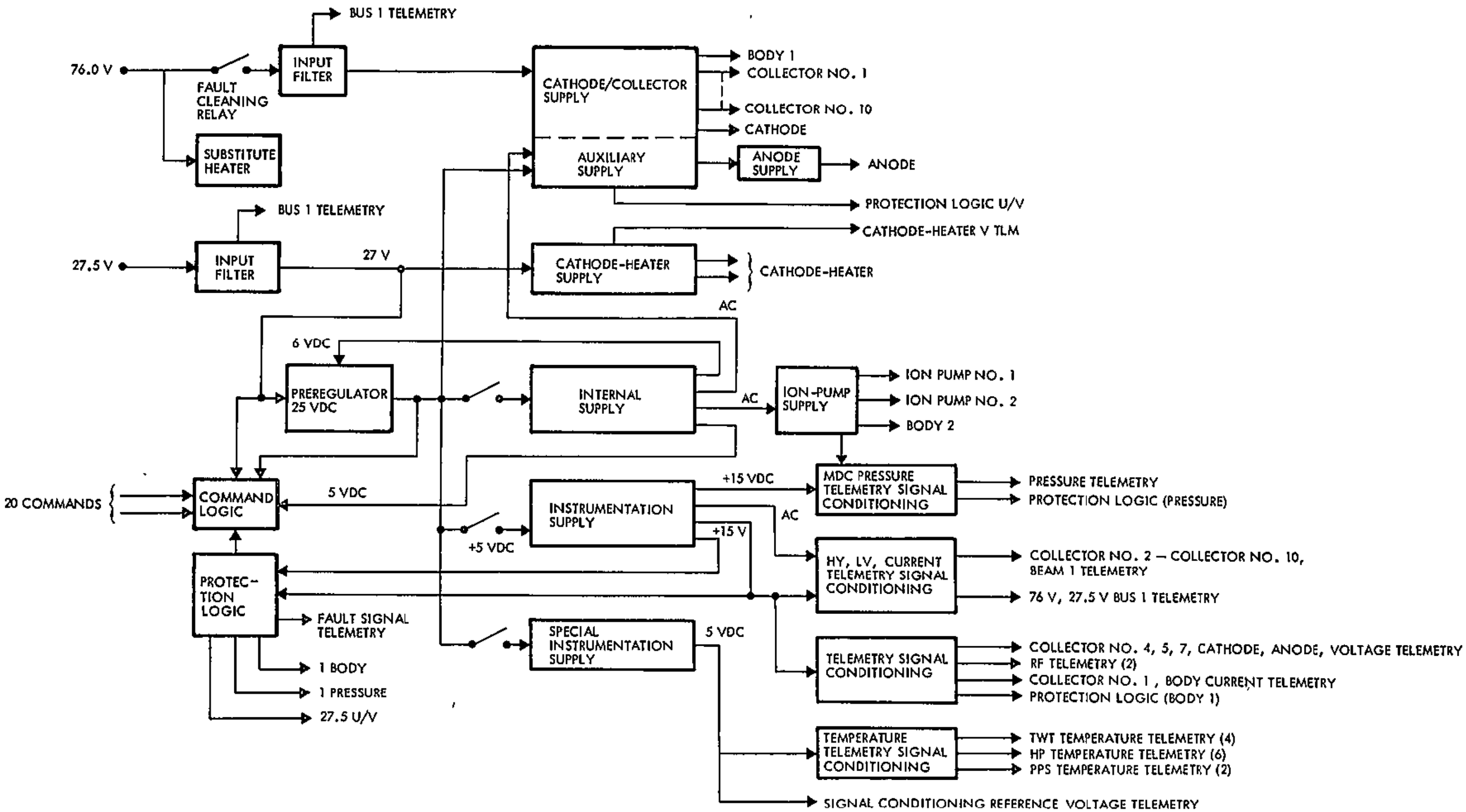


Figure 2-1. PPS Simplified Block Diagram

Basic turn-on of the TEP is accomplished by commanding cathode heater power to full output from a standby half-power condition, providing a time delay to permit thermal stabilization of the cathode heater, and then followed by a command that simultaneously energizes cathode/collector and anode outputs. The protection logic acts to disable the TEP in an orderly manner under conditions of bus under-voltage, excess body current, or excess MDC pressure.

The telemetry system provides 37 signals for monitoring TEP status. The signals provided correspond to the following parameters:

- Currents. Collectors 1 to 10, beam, body, 76 volt bus, 27.5 volt bus.
- Voltages. Cathode heater, anode, cathode, collectors 4, 5, and 7, signal conditioning reference voltage (+5 volts for temperature monitors).
- Temperatures. 2 for PPS, 4 for TWT, 6 for TEP heat pipe system.
- Miscellaneous. MDC pressure (ion pump supply current), RF output power (forward), RF output power (reflected), fault signal (indicating type of fault shutdown).

3. REQUIREMENTS

This section contains the detailed design requirements (electrical, mechanical, and environmental), of the TEP, including the VCHPS. Many of the TEP requirements evolved during the course of the development program. The final OST design represented a considerable advance in the previous technology of space-type traveling wave tube amplifiers. The high power level (up by an order of magnitude) in combination with the need for new high voltage power electronics circuit techniques and components resulted in several modifications to baseline requirements that ultimately led to a high power transmitter system design that successfully met all program objectives.

The design requirements, along with appropriate comments, are summarized in the following order: electrical (PPS to spacecraft interface and PPS to OST interface), mechanical (including VCHPS), environmental, and reliability/ fail safe.

3.1 ELECTRICAL

3.1.1 PPS to Spacecraft

Input power for TEP is derived from two spacecraft sources: an experimental bus for the major TEP loads (OST cathode-collector supply, substitute heaters); and a housekeeping bus for the cathode heater, ion pump, and instrumentation loads. The anode supply and cathode-collector supply drive power may be derived from the housekeeping bus. The experimental bus is derived from a solar array, sized primarily to supply TEP power requirements which, by a large margin, exceed other experimental bus loads.

3.1.1.1 Input Voltage Limits

	Experimental Bus	Housekeeping Bus
Normal operation	76 ±11 Vdc	27.5 Vdc ±3%
No damage	Up to 95 Vdc	Up to 42 Vdc

With regard to the experimental bus, the higher than normally encountered nominal bus voltage level (76 Vdc) reflects a value that is consistent with the high TEP power rating (>500 watts). This voltage level reduces TEP steady state input current to less than 10 amps and does not compromise the selection of suitable power semiconductor switching devices required in the TEP design. The voltage range (65 to 87 Vdc) is consistent with the expected variations in solar array voltage due to load (no load to full load) and temperature. The requirement for TEP operation from an unregulated bus avoids the weight penalty associated with a regulated bus approach, in which power source regulation means must be included in the spacecraft power system design.

The "no damage" limit of 95 volts on the experimental bus is derived from the overvoltage cutout setting of a spacecraft bus switch upstream of the TEP. This switch protects equipment from exposure to the high solar array eclipse exit voltage of approximately 140 Vdc.

3.1.1.2 Input Power

The PPS must be capable of powering a 50 percent efficient OST that produces a maximum level of 240 watts RF. Coupled with the PPS efficiency requirement (next paragraph), this results in an experimental bus power demand of 565 watts maximum. Under nominal operation, 200 watts RF, a 471 watt power demand was forecast.

Power from the housekeeping bus must not exceed the following values under the indicated TEP operating conditions:

- Spacecraft sunlight (cathode heater and special instrumentation on, operating from housekeeping bus) 29.5 W
- Eclipse (cathode heater at half power and special instrumentation on) 9.0 W
- Eclipse (special instrumentation only). 1.0 W

These limits were established to minimize the impact on the available spacecraft housekeeping bus design.

3.1.1.3 Efficiency

PPS conversion efficiency at OST saturation must be 85 percent or greater. Conversion efficiency is defined as dc power to the OST divided by total dc power input to the PPS, less power required for command, instrumentation, and telemetry functions.

High efficiency is critical in achieving minimum system weight because of its impact on the design of the unit thermal dissipation approach and because the solar array must be sized to accommodate any losses.

3.1.1.4 EMC

The TEP must be designed to conform to the requirements for EMC as outlined in MIL-STD-461A, Notice 1 for Class I equipment, with the following exceptions:

a) Narrowband power line conducted interference (both power buses), design per limits given in MIL-STD-461A, Notice 3. This requirement, of special importance in PPS input filter design, limits power line feedback ripple current to 10 mA, peak at 20 kHz, the switching frequency selected in the PPS regulator design.

b) Conducted susceptibility (both power buses), design per limits given in MIL-STD-461A, Notice 3. This requirement calls for specified performance with imposed power line audio ripple of 2 V rms from 30 to 6500 Hz, decreasing to 1 V rms at 50 kHz.

c) Single event power line switching transients (both buses). Except during input filter charging, single event switching transients must be limited to a 20 percent change above/below normal operating voltage for on/off transients in power/signal lines. (Pulse duration, 10 to 90 percent points, of $\leq$0.1 msec; source impedance assumed between 0.1Ω to 1Ω).

d) Turn-on surge currents (either power bus) must be limited to no more than 125 percent of nominal operating current. In this application, the TEP load dominates the total load on the unregulated experimental bus and, therefore, in-rush current level is a parameter of more than passing significance because of its impact on solar array sizing. Typically encountered TWT turn-on surge currents (several times nominal steady state current) are unacceptable for the TEP to avoid the large source overdesign that would be necessary to provide the turn-on energy requirement. Imposition of the tighter in-rush requirement, in part, led to the design of a PPS with current source characteristics, as described in Section 4.

3.1.1.5 Grounding

The PPS provides for an isolated grounding system wherein all grounds — 76 and 27.5 volt input power, command, telemetry and output power — are isolated from each other and, except for output ground, are isolated from the PPS chassis.

The isolated grounding concept evolved from the recognition that inherent in any high voltage design, the possibility exists that arcing may occur with attendant coupling of unwanted energy in noise-sensitive signal lines and, thence, into the spacecraft command and telemetry systems. In combination with appropriate shielding techniques, the TEP grounding concept permits the achievement of a noise immune system.

3.1.1.6 Commands

Twenty commands are required for operation of the TEP. These commands (pulse type) are routed to the PPS for operation of the system. The large number of commands are derived from the desire to achieve maximum operational flexibility with an experimental system.

Table 3-1 identifies the required TEP commands. Three of 20 commands are associated with enabling or disabling the PPS and/or the substitute heaters, seven with energizing and/or adjusting PPS output supplies, two with activation of instrumentation functions, five with protective functions, two with TEP fault clearing, and one related to TEP failure mode operation. Command functions are described in detail in Section 4.

The commands provided are digital signals with the following characteristics:

Logic "one" (command)	+3.8 to 5.5 V (3.8 V min at 10 mA load)
Logic "zero" (no command)	0 to 0.6 V
Pulse duration	50 msec ±2%
Input impedance	>250 Ω, <300 pf
Source capability	20 mA (short circuit)
Rise/fall times (10 to 90 percent)	10 to 1000 μsec
Isolation	Command system is isolated from system high voltages

Table 3-1. Command Identification

Close TEP Experimental Bus Switch
Open TEP Experimental Bus Switch
PPS Enable
PPS Disable (Substitute Heaters On)
Special Instrumentation On
All Instrumentation Off
Cathode Heater at 50 Percent Power (Substitute Heaters On)
Cathode Heater at 100 Percent Power
Cathode Heater at 110 Percent Power
Cathode Heater at 120 Percent Power
Cathode Heater Off (Substitute Heaters On)
Anode/Cathode-Collector Supply On
Anode/Cathode-Collector Supply Off (Substitute Heaters On)
Defeat Excess Pressure Protection
Defeat Excess Body Current Protection
Protection On (Body Current, Pressure) and Fault TLM Reset
Preregulator Bypass On
Substitute Heaters Off
High Voltage Protection On
High Voltage Protection Off

Required command sequencing is discussed in Section 4. The following command interlocks must be provided:

a) The TEP experimental bus switch is not capable of operation while the experimental bus is powered. The TEP bus switch, described in Section 3.1.1.8, does not have to clear a TEP fault instantaneously because of the upstream bus protection provided in the spacecraft power system. By precluding the switch from operating (make or break) under power, a minimum size space-qualified relay can be used for this function.

b) When the cathode heater is a half power, the anode/cathode-collector on command cannot be activated. (The latter can be activated for cathode heater at 0, 100, 110, 120 percent power). The high voltage anode/cathode-collector outputs can be activated only with the cathode heater set at the full power settings (100, 110, 120 percent), the normal condition, or at zero cathode heater output. The latter, equivalent to no load operation of the PPS, is not deleterious to the unit and is included to allow application of high voltages to the OST in space for diagnostic purposes. By applying high voltages with no beam current present, leakage at the various OST electrodes can be monitored via telemetry.

c) Automatic shutdown of the anode/cathode-collector voltages occurs if the cathode heater is commanded off or to half power. This feature is required to preclude OST beam defocusing and consequent excessive OST body current during normal system shutdown.

3.1.1.7 Telemetry

The PPS must furnish power for all TEP telemetry and signal conditioning functions. Calibrated analog voltages are provided to the spacecraft telemetry system proportional to the 37 measured parameters listed in Table 3-2. The large number of signals were included to more fully diagnose long term on-orbit performance of the TEP. This requirement, along with the large number of commands, resulted in heavier TEP weight (by approximately 6 pounds) than would be required by an operational system.

"Special Instrumentation" consists of a group of 12 TEP temperature measurements which are powered and controlled separately. The telemetry parameters in this group consists of Nos. 19 through 24 and 30 through 36. Parameter No. 30 is the voltage used to power the temperature sensing networks.

The telemetry signal output voltage range shall be 0 to +5 Vdc and have a full scale accuracy of ±1 percent. Telemetry channel output impedance shall not exceed 5 KΩ.

3.1.1.8 Input Protection

The design of the PPS must be such as to shut down and not restart automatically if potentially damaging abnormal voltages appear on either input power bus. Details on the implementation of abnormal bus voltage protection are presented in Section 4.

A fault clearing relay shall be included in the PPS experimental bus input to provide commandable disconnect capability. This switch is not required to connect or disconnect the TEP when the experimental is powered. Under TEP fault conditions, an upstream spacecraft bus switch will open before the TEP fault clearing relay is commanded off. Conversely, the TEP

Table 3-2. Telemetry Signal Requirements

No.	Parameter	Range	
1	Cathode Heater Voltage	0 to 10 Vdc	
2	Cathode Voltage	0 to -15 k Vdc	
3	Beam Current	0 to 100 mA	
4	Body Current	0 to 15 mA	
5	Anode Voltage	0 to 600 Vdc	
6	Collector 4 Voltage	0 to -10 k Vdc	
7	Collector 5 Voltage	0 to -10 k Vdc	
8	Collector 7 Voltage	0 to -10 k Vdc	
9	Collector 1 Current	0 to 15 mA	
10	Collector 2 Current	0 to 15 mA	
11	Collector 3 Current	0 to 25 mA	
12	Collector 4 Current	0 to 25 mA	
13	Collector 5 Current	0 to 25 mA	
14	Collector 6 Current	0 to 25 mA	
15	Collector 7 Current	0 to 25 mA	
16	Collector 8 Current	0 to 40 mA	
17	Collector 9 Current	0 to 40 mA	
18	Collector 10 Current	-10 to +5 mA	
19	PPS Component Temperature	-55 to +150°C	
20	PPS Baseplate Temperature	-55 to +100°C	
21	TWT Body Temperature	-15 to +150°C	Sensors in OST
22	MDC Collector Temperature, Position 1	+25 to +225°C	Sensors in OST
23	MDC Collector Temperature, Position 2	-15 to +150°C	Sensors in OST
24	Coupler Temperature	-15 to +150°C	Sensors in OST
25	Reflected RF Power	0 to 25 W	Sensors in OST
26	Forward RF Power	0 to 250 W	
27	Envelope Internal Pressure	0 to 10 μA	
28	Housekeeping Bus Current	0 to 1.5 amp	
29	Experimental Bus Current	0 to 10 amp	
30	Signal Conditioning Reference Voltage	0 to +5 Vdc	
31	Heat Pipe 6 Temperature	+150 to +200°F	
32	Heat Pipe 1 Temperature	-100 to +175°F	
33	Heat Pipe 2 Temperature	-100 to +175°F	
34	Heat Pipe 3 Temperature	-100 to +175°F	
35	Heat Pipe 4 Temperature	-100 to +175°F	
36	Heat Pipe 5 Temperature	+150 to +200°F	
37	Shutdown Fault Indicator	5 V level indicates "normal" 3 V level indicates pressure trip 1.5 V level indicates body current trip 0 V level indicates undervoltage trip	

switch will be commanded on before the spacecraft bus switch is closed. The TEP relay contacts must be rated to carry a nominal 9 amps (17 amps for 30 sec) and withstand 200 volts in the open position.

The experimental bus also powers a 20 watt K-band TWTA, not part of the TEP, which serves as the driver to the OST. The inclusion of the fault clearing relay in the TEP permits the usage of the driver for transmission in the event of TEP failure.

3.1.2 PPS to OST

The PPS must provide conditioned power at differing voltages to the various elements of the OST and to two ion pumps which maintain vacuum conditions in the multistage collector assembly. Detailed electrical requirements for each PPS output follow.

3.1.2.1 Cathode Heater Supply

The PPS cathode heater supply must provide a well regulated dc current output to the OST cathode heater. Requirements are:

Power source	Housekeeping bus
Nominal output voltage	4.2 Vdc (at -11.3 k Vdc to ground)
Nominal output power	5.9 watts
Maximum output power	7.0 watts
Regulation (current)	±1% (over line, load and temperature)
Ripple	2% pk-pk
Output current limit (including startup)	1.5 amps
Output adjustment	Adjustable by command for set points of 50, 100, 110, 120 percent of nominal output power

The output current limit provides for a "soft start" characteristic during cathode heater turn-on, desirable for filament type loads. The output adjustment settings were required because of the experimental nature of this application.

It is desirable to switch to cathode heater half power during shutdown of the TEP. This precludes the large cathode temperature swings that would ensue in removing power entirely during dormant periods and prevents the condensation of contaminants on the cathode element.

3.1.2.2 Cathode-Collector Supply

The PPS high voltage supply must provide a well-regulated, adjustable cathode-to-body voltage with extremely low ripple and multiple high voltages with less stringent regulation and ripple requirements for the OST collector assembly. As discussed in Section 4 (System Design Considerations), a common high voltage cathode/collector supply with series connected outputs was selected as the optimum concept. The detailed electrical requirements listed below conform to this configuration wherein the collector supplies listed, in sum, comprise the cathode-to-body output, with the OST body (ground potential) common with the collector 1 potential and the OST cathode in common with collector 10. The power source for this combined supply must be the experimental bus.

Collector Supply	Voltage (Vdc)	Collector Supply Current (mA)			Collector Number	Voltage To Ground (k Vdc)
		ORF	NOM	MAX		
1-2	2260	2	6	12*	1(and body)	0
2-3	1130	2.5	10	17	2	-2.26
3-4	1130	3	20	29	3	-3.39
4-5	1130	3.5	35	45	4	-4.52
5-6	1130	4.5	44	53	5	-5.65
6-7	1130	6	50	57	6	-6.78
7-8	1130	8	55	63	7	-7.91
8-9	1130	27	60	65	8	-9.04
9-10	1130	72	72	72	9	-10.17
					10(and cathode)	-11.3

*Body current = 4 mA max
Collector 1 current = 8 mA max

Static voltage regulation and output ripple requirements placed on the cathode-to-body and collector-to-cathode voltages are:

	Regulation (Percent)	Ripple (Percent pk-pk)
Cathode-body	±1.0	0.01
Collector-cathode	±3.0	2.0

Static regulation covers the allowable voltage variation over the normal range of PPS input bus voltages and is power quality, the load change reflected through operation of the OST from zero RF drive to saturation and PPS operating temperature limits. Under no load or open circuit conditions (no OST beam), the collector-cathode voltages are permitted a larger variation, not to exceed ±10 percent of nominal values. An extremely low ripple requirement is placed on the cathode-body output, approximately 1 volt out of 11.3 KV.

A step turn-on response requirement of 40 msec or less was placed on the high voltage cathode-body and collector-cathode PPS outputs. Dynamic load regulation requirements in terms of response to step RF load changes (ORF to saturation) was 10 msec.

Adjustment requirements were ±3 percent for the cathode-body output while collector-cathode voltages were permitted to vary proportionately to the cathode-body voltage.

The power rating of the PPS high voltage outputs (neglecting anode and ion pump supplies which total less than 1 watt) can be calculated by summing the products of individual collector supply voltage and current ratings for each load condition. The calculations yield 481, 405, and 148 watts respectively, for the maximum saturation, nominal saturation, and zero RF drive conditions.

3.1.2.3 Anode Supply

The PPS anode supply must provide a well regulated, adjustable voltage to the OST anode. Requirements are:

Nominal output voltage	+350 Vdc
Load range	0 to 0.1 mA

Regulation (voltage)	±1 percent (over line, load, temperature)
Ripple	0.5 percent pk-pk
Output voltage adjustment range	+150 to +550 Vdc

3.1.2.4 Ion Pump Supply

The PPS ion pump supply must provide power to operate two ion pumps each having the following electrical requirements:

Nominal output voltage	+3.3 K Vdc at 10 μA/pump
Load range (per pump)	0 to 50 μA*
Regulation (voltage)	10 percent
Ripple	10 percent pk-pk

A further requirement is that a short-to-ground failure of one pump must not prevent normal operation of the remaining pump. Supply output voltage must not drop below 2500 volts under this condition.

3.1.2.5 Output Protection Requirements

The PPS protects the load by limiting the amount of energy that can be delivered under abnormal momentary load conditions by separately sensing body current and ion pump current (pressure) and automatically turning off the PPS high voltages when body current exceeds 10 mA, ±1 mA for 10 msec, ±1 msec or ion pump current exceeds 10 μA ±1 μA. The TEP must remain off, except for the cathode heater supply (after shutdown occurs) until the TEP is reset and restarted.

Energy delivered to the OST structure during an arc must be less than 10 joules and peak currents limited to less than 100 amps. Commands must be provided to separately disable the body current and ion pump current protection trip circuits to permit TEP operation should fault signals be erroneously generated (see Section 3.1.1.6).

*An ion pump current of 25 μA corresponds to a pressure of approximately 5×10^{-5} torr.

In the event of an automatic shutdown of the PPS, a telemetry measurement must identify, by voltage level, the following causes of shutdown (Section 3.1.1.7):

Input bus undervoltage

Excess body current

Excess ion pump current.

The PPS must have an inherent load current limiting capability which provides self-protection from load transients, permanent fault conditions, and/or progressive overloads. It must not be damaged or overstressed by any single or multiple combination of specified input source and/or output load conditions occurring at the respective terminals, including single or multiple terminal short circuits.

3.1.2.6 Signal Conditioning Requirements

The PPS must provide signal conditioning for all the telemetry parameters listed in Section 3.1.1.6, including the sensors external to the PPS (pressure, temperature, and RF power in the OST and temperature in the VCHPS).

a) Temperature Sensors

The PPS must supply a 5 Vdc ±1 percent regulated voltage, designated "signal conditioning reference voltage," and the appropriate resistor divider network for all TEP thermistors. A maximum current of 1 mA per thermistor channel is required.

b) Pressure Sensor

The PPS must supply the power and the appropriate signal conditioning circuitry for the OST internal pressure transducer. This consists of sensing the current drawn from the ion pump supply. The requirements for this supply are described in Section 3.1.1.6.

c) OST RF Power Sensors

The PPS must condition the RF power measurements (reflected and forward) originating from directional couplers in the OST output waveguide. The sensors provide signal voltages in the range of 0 to 250 mW and must be presented with 5 KΩ impedances at the PPS interface.

3.1.3 Substitute Heater Electrical Requirements

A substitute or replacement heater system must be provided in the TEP to maintain acceptable temperatures within the PPS and OST body when the TEP is in a powered-down condition. This thermal control system, contained in the PPS, and associated heater elements must be powered from the experimental bus. It must be automatically energized whenever the TEP is commanded off (PPS disable command), when the high voltages are off, or when the cathode heater is off or at 50 percent power. It must also be capable of being commanded off. Heater circuits must be fused to protect the bus.

3.2 MECHANICAL

3.2.1 General

The TEP and its associated VCHPS are installed onto the CTS spacecraft as illustrated in Figure 3-1(a). The PPS baseplate mounts directly to the spacecraft south panel and extends to spacecraft hard points at each corner, as illustrated. In turn, the OST tube body mounts adjacent to the PPS enclosure and bolts to the PPS baseplate through the intermediate VCHPS evaporator saddle. The OST multistage depressed collector (MDC) structure, which is thermally isolated from all other TEP components, is cantilevered off the OST tube body and exposed to the space environment through a cutout in the aft panel of the spacecraft.

In this approach, the PPS and OST tube body enclosures can be treated as integral structural members capable of transferring launch loads directly to the four south panel hardpoints. Overall structural efficiency of the spacecraft is accomplished by such dual usage of the relatively large structure in lieu of the heavier approach of stiffening up the spacecraft south panel.

Power dissipated within the PPS enclosure is conducted through the south panel honeycomb structure and radiated to space. Since the south panel radiative capacity is limited, electrical dissipation within the OST tube body is conducted into the VCHPS evaporator saddle and conducted through three parallel heat pipes to the VCHPS radiator panel where it is rejected to space. This radiative extension to the south panel is designed and supported such that south panel loads are not transmitted to the critical spacecraft forward platform and/or forward thrust tube via the

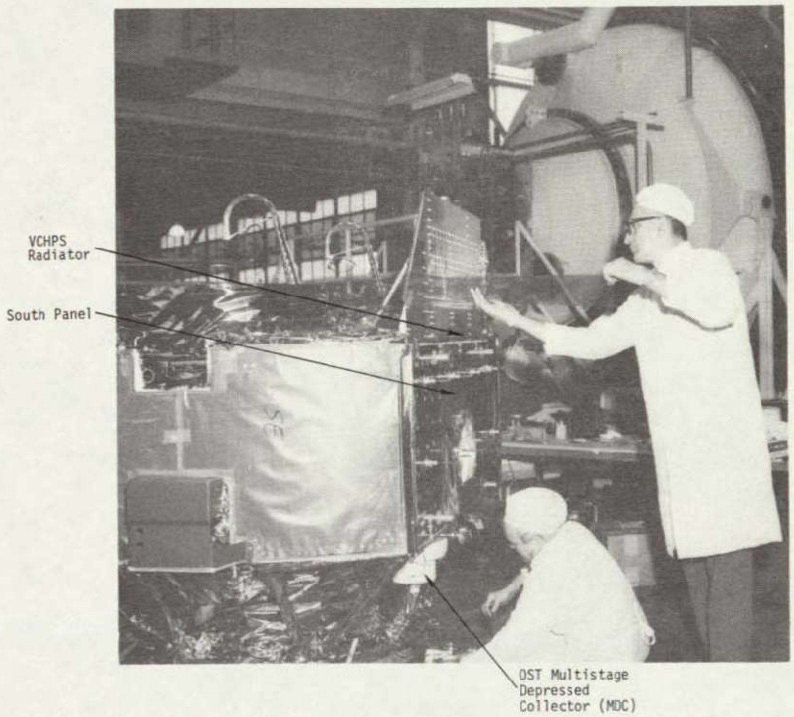


Figure 3-1 a). CTS Spacecraft Looking at South Panel

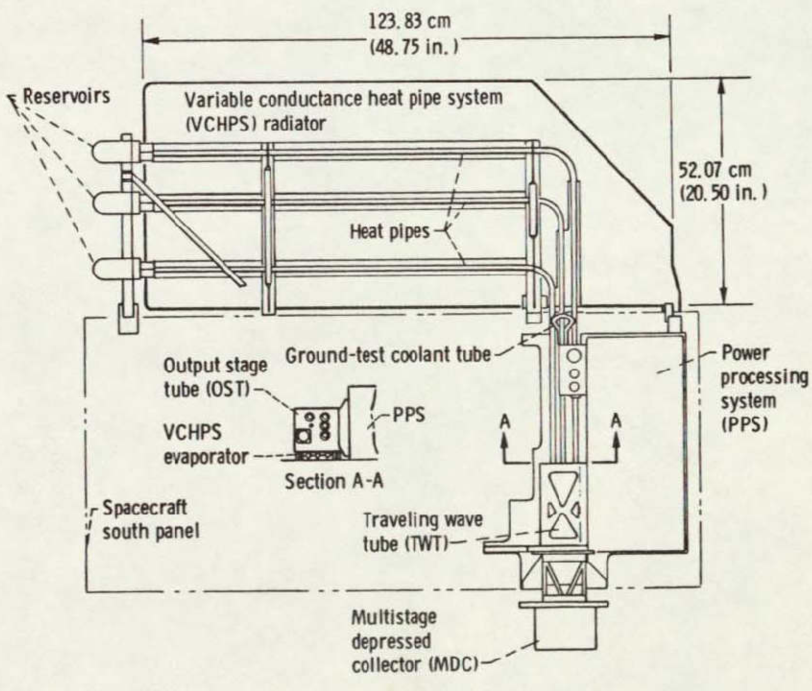


Figure 3-1 b). Top View of Inside Surface of South Panel

VCHPS heat pipes or radiator support structure. The only loads to be reacted with the forward platform are those associated with the radiator mass. The VCHPS radiator and associated support structure mount to the south panel at the five hardpoints illustrated in this figure.

Power dissipated within the PPS enclosure is conductively-coupled through the spacecraft south panel and radiated directly to space. The OST tube body is cooled by conduction into the VCHPS evaporator saddle and through the three heat pipe system to the radiator fin extension on the south panel where it is radiated to space. Any dissipation within the MDC is directly radiated to space without any intermediate conduction or radiator paths, since the MDC is exposed directly to the space environment.

3.2.2 Mass Properties

The TEP weight (in pounds) is as shown below:

OST body	13.32
OST MDC	12.87
OST	26.19
TEP	55.47
VCHPS off, south panel	12.6
VCHPS on, south panel	3.8
VCHPS	16.4
TEP and VCHPS nominal mass	71.87
Uncertainty	0.73
Maximum allowable	72.60

3.2.3 Envelope

The PPS enclosure envelope is limited to 7 inch height x 9.5 inch width x 20.5 inch length. The baseplate envelope is within the dimensions specified in Figure 4-10 to allow adequate space for other south panel equipment.

The VCHPS radiator fin fits within the envelope specified in Figure 3-2 to prevent interference with the SAF antenna patterns and/or the launch vehicle shroud. VCHPS radiator design allows for detachment of the radiator fin from the heat pipe subassembly without recharging the heat pipe. Such an operation is performed after the entire subsystem is mounted on the spacecraft. This feature allows for either modification or rework of the radiator fin during spacecraft integration and test without causing any negative impact on the overall program schedule.

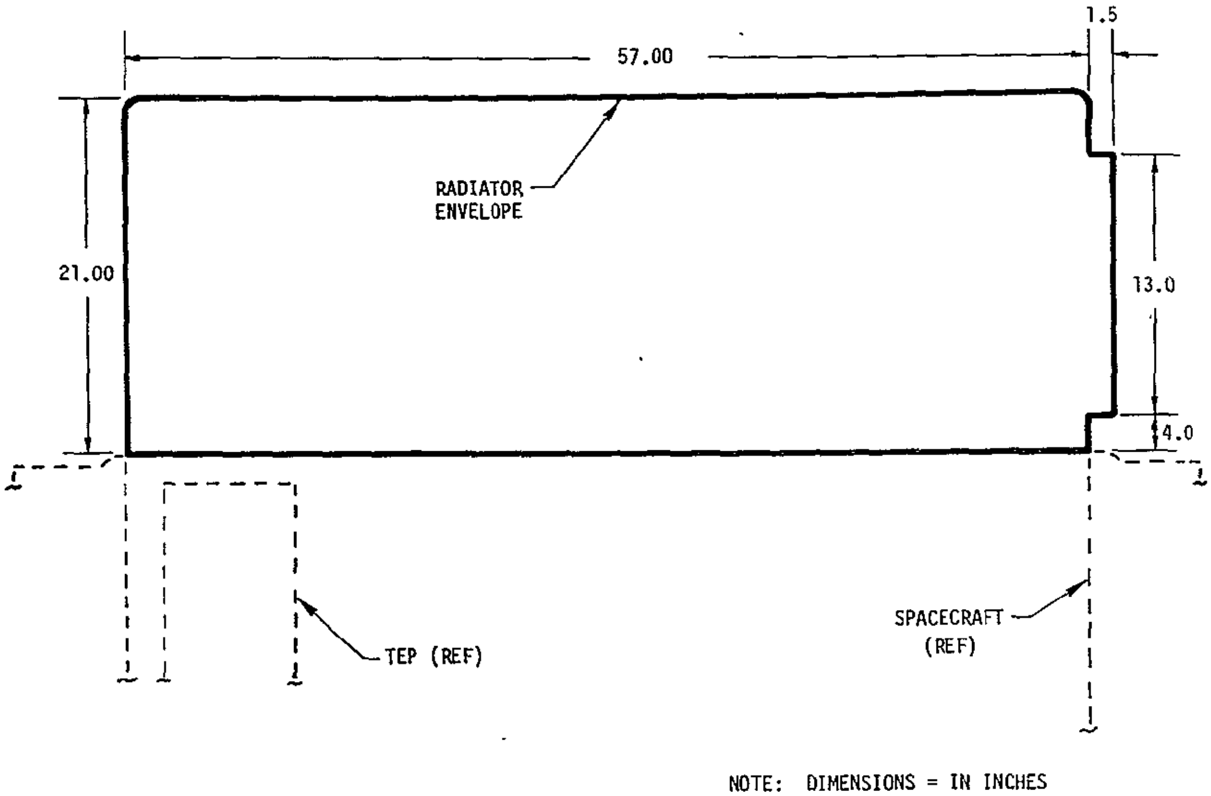


Figure 3-2. VCHPS Radiator Envelope

3.2.4 Venting

The PPS and OST are vented to the interior of a TEP zone blanket. The interior of the zone blanket is vented around the MDC directly to space. Before the TEP is turned on, the pressure within 5 cm of all PPS and OST venting holes is less than or equal to 1×10^{-5} torr. The outgassing time for the spacecraft to reach this maximum allowable turn-on pressure is 48 hours, as determined by the reading of ion gases within the TEP zone blanket in the engineering model spacecraft thermal vacuum test.

3.2.5 Packaging

The TEP is designed to operate continuously in space for 2 years. Operation in either vacuum ($\leq 1 \times 10^{-5}$ torr) or ambient conditions is provided to permit ground testing. The TEP is not required to operate at any pressures in between vacuum and ambient. To minimize PPS weight and maximize reliability, open construction design for packaging high voltage components is preferred. All high voltage components are designed for a 2:1 voltage derating.

Bendix JT connectors are provided for each of the following groups of wires:

- Experimental bus power to PPS
- Housekeeping bus power to PPS
- OST telemetry inputs to PPS
- Spacecraft commands to PPS
- TEP telemetry to spacecraft.

3.2.6 Structural

The TEP and VCHPS must be capable of enduring spacecraft launch and environmental test program loads without any structural damage. As part of this structural design, the subsystem natural frequencies should be separated from other spacecraft or launch vehicle critical frequencies. To achieve this, it was a design goal to produce a TEP design with a natural frequency of 150 Hz or more when the TEP is supported at the four corner hard support points. During TEP qualifications or acceptance testing,* if $f_n \geq 150$ Hz, test response cutoff for the MDC was 20 g. If $f_n < 150$ Hz, MDC notching at 35 g was carried out.

There is no requirement for natural frequency for the VCHPS radiator fin assembly, but is is pointed out that the launch vehicle POGO axial vibration input is within the region of 17 to 23 Hz, the spacecraft plus adapter axial modes are in the region of 35 to 70 Hz. Consequently, it is undesirable to have the radiator fin dynamically coupled with any of the above resonant modes.

*See Section 5 for test levels.

The TEP is designed for ultimate load of 56 g in any of three axes and a yield load of 45 g. The VCHPS is designed for an ultimate load of 75 g in any of three axes and a yield load of 60 g. A factor of safety of 1.0 is acceptable at these design loads.

3.2.7 Thermal

The TEP thermal control system is designed to dissipate the power levels specified in Table 3-3, while maintaining the TEP equipment at the temperature specified in Table 3-4, for the design conditions listed in Table 3-5. The thermal properties of the south panel are listed in Table 3-6. Details of the VCHPS thermal design and spacecraft environmental conditions are presented in Section 6 of this report.

Table 3-3. TEP Power Dissipation (Watts)

Condition	OST		PPS		VCHPS
	Tube Body	MDC	Substitute Heater On	PPS (Internal)	
Normal operating; saturated RF drive	161	54	0	71	0
Standby; cathode heater half power and special instrumentation on	3	0	0	6	0
Standby; cathode heater half power	3	0	0	1	0
Standby; substitute heater on	0	0	75 ±20*	0	0

*Actual level depends on experimental bus voltage level, which can vary between 65 and 87 volts.

Table 3-4. Allowable TEP Temperature Levels

Condition	OST			VCHPS
	PPS Baseplate	Tube Body	MDC	
Minimum, nonoperating	$-20^{o}C$	$-20^{o}C$	$-125^{o}C$	$-150^{o}C$
Minimum, turn-on	$-10^{o}C$	$0^{o}C$		N/A
Minimum, operating	$0^{o}C$	$0^{o}C$		$-150^{o}C$
Maximum, operating	$56^{o}C$	$58^{o}C$		$+60^{o}C$
Maximum, nonoperating	$65^{o}C$	$65^{o}C$		$+60^{o}C$

Table 3-5. Thermal Design Conditions

<u>Steady State</u>

a) Winter and/or summer solstice, local midnight, maximum power

b) Summer solstice, noon, substitute heaters only

c) Equinox, full equipment power prior to eclipse, sun normal to forward platform

d) Equinox, substitute heaters on prior to eclipse when all power is off

<u>Transient Cases</u>

a) Maximum eclipse, followed by warmup, no power. Use initial condition as coolest of a) – d) above

b) Winter and/or summer solstice, full power 6:00 p.m. – 6.00 a.m. (hot case of a) or b)

Table 3-6. South Panel Thermal Properties

Face sheet to face sheet	$K/\ell = 9 \pm 3 \dfrac{BTU}{hr\text{-}ft^2 - {}^oF}$	
Lateral forward to aft	$K/\ell = 0.037 \dfrac{BTU}{hr\text{-}ft^2 - {}^oF}$	
Lateral east to west	$K/\ell = 0.056 \dfrac{BTU}{hr\text{-}ft^2 - {}^oF}$	
Exterior surface thermal properties	$\alpha = 0.14 \pm 0.06$	$\varepsilon = 0.80 \pm 0.01$
Interior surface thermal properties		$\varepsilon = 0.04 \pm 0.01$

3.3 RELIABILITY AND FAIL SAFE REQUIREMENTS

3.3.1 Reliability

The PPS must have a reliability of 0.9 or greater for 2 years of operation in space.

3.3.2 Fail Safe

The PPS must enhance the reliability of the TEP by the inclusion of several features designed to achieve a measure of fail safe performance of the unit. These features provide a means of overcoming credible failures in those portions of the PPS not critical to its basic operation. The requirements are:

a) Ion Pump Supply Fail Safe

The ion pump supply must be capable of tolerating and operating satisfactorily in the event one of the two OST ion pumps fails in a shorted condition. Further, failure of both pumps cannot prevent normal operation of the PPS, it being possible to continue TEP operation in this condition.

b) <u>Anode Supply Fail Safe</u>

The anode supply must be capable of tolerating an output (anode) short to ground without disabling the PPS. Further, in the event of an open in the anode supply, means must be provided to prevent the OST anode from approaching cathode potential, thereby causing beam current cutoff.

c) <u>High Voltage Telemetry Fail Safe</u>

Momentary shorts in the PPS high voltage telemetry sensing resistors must not prevent normal operation of the PPS nor damage the spacecraft telemetry system.

d) <u>Preregulator Fail Safe</u>

The PPS includes a 25 volt series preregulator powered from the housekeeping bus. This preregulator, supplying in part the anode supply and drive power for the cathode/collector supply, was included to provide regulation in the event of abnormally high input voltages. The critical preregulator pass transistor can fail short without deleterious effect on PPS operation under normal input voltage conditions. It was a requirement that means be provided to ensure normal PPS operation up to 30.5 Vdc on the housekeeping bus, in the event of a preregulator open.

4. POWER PROCESSOR SYSTEM DESIGN

4.1 SYSTEM DESIGN CONSIDERATIONS

The critical interface requirements that must be addressed in the design of a high power TWT power processor relate not only to the special nature of a high voltage TWT load but also, because of the high power handling capability involved, to the effect on power source characteristics and on spacecraft thermal and structural design. The significant interface requirements between power processor and respectively, OST load, power source, and spacecraft are identified and/or discussed in the following.

a) Power Processor System and OST. The major requirements on the PPS at the output interface are:

- The need for multiple, variable loaded, high voltage outputs for the OST depressed collector assembly
- Stringent regulation, ripple, and output impedance requirements on the cathode-to-body voltage
- OST startup characteristics and requirements (sequencing of output voltages, output rise time)
- Protection for the OST during turn-on and other conditions when excess body current is drawn, such as high voltage arcing
- Safe operation of the power processing (and spacecraft electrical systems) while exposed to an arcing OST.

b) Power Processor System and Source. At the source interface, the major requirements are:

- Inrush current control during startup and output fault conditions
- Audio susceptibility control
- Conducted interference control
- High efficiency to minimize complexity of thermal design and reduce the rating of the power source.

c) Power Processor System and Spacecraft. The magnitude and concentration of both PPS and OST power dissipation and total mass requires that an integrated thermal and structural approach be pursued in the spacecraft design.

In the thermal area, the high dissipations encountered during operation in both PPS and OST (up to 225 watts) require that critical components be carefully located and thermal control be exercised to divert dissipation to the radiator system. Also, active thermal control is required to maintain minimum rated temperatures during nonoperating periods and to prevent unacceptable low temperatures from being reached in the power processor and TWT.

In the structural area, the OST collector assembly presents a cantilevered load off the spacecraft mounting panel. Support members must be provided for internal load distribution to ensure structural integrity of large power processor high voltage components and the TWT structure. Since the baseplate of the TWT may span spacecraft hard points, truss members may be required to carry TWT structural loads to the hard points. Adequate TWT stiffeners must also be provided to ensure that the resonant frequency is higher than the lowest spacecraft excitation mode.

4.2 DESIGN CONCEPT

The selection of an optimum PPS electrical design concept or configuration that minimizes weight and complexity and provides high reliability, primarily rests with implementation of the high voltage supplies. This, in turn is strongly affected by OST startup requirements. Turn-on of the OST via anode switching was evaluated along with the conventional technique, diode turn-on. In the latter, all required high voltages (cathode, collectors, and anode) are switched on simultaneously with an attendant overshoot in body current occurring as the cathode-to-body potential builds up to the related level (200 to 300 percent in 2 to 3 msec, typically). With anode switching, body current overshoot on startup is avoided since the electron beam is initiated when the OST anode is switched from a previously established negative cathode potential to the positive bias level required.

The conventional approach of a common high voltage cathode/collector supply with series connected outputs, providing the precision cathode-to-body requirement and the lesser regulation and ripple requirements of the collector voltage outputs, was selected on the basis of minimum power stage part count and weight. This configuration allows all high voltage outputs to be turned on simultaneously, thus eliminating the complexity associated with an anode switched configuration (or possible component problem if designed with a high voltage relay).

Among other advantages of the selected approach are:

a) Turn-on body current surges are easily accommodated by the high power capacity of the common cathode/collector supply, a problem in configurations embodying a separate cathode-body-supply.

b) Collector voltages are always maintained at fixed fractions of the cathode-to-body voltage, including turn-on; this is desirable from the standpoint of OST operation and greatly minimizes the circuit complexity associated with separate supplies.

c) The series connection of outputs results in minimum stress levels on high voltage components.

d) A load is maintained on the common supply under any RF drive condition including zero drive.

A widely varying load characteristic is presented to the PPS collector outputs over the full range of RF drive, but total beam current remains constant. The common supply effectively sees only an approximate 3:1 load change from zero to the full RF drive condition. Figure 4-1 illustrates the connection of individual PPS output supplies.

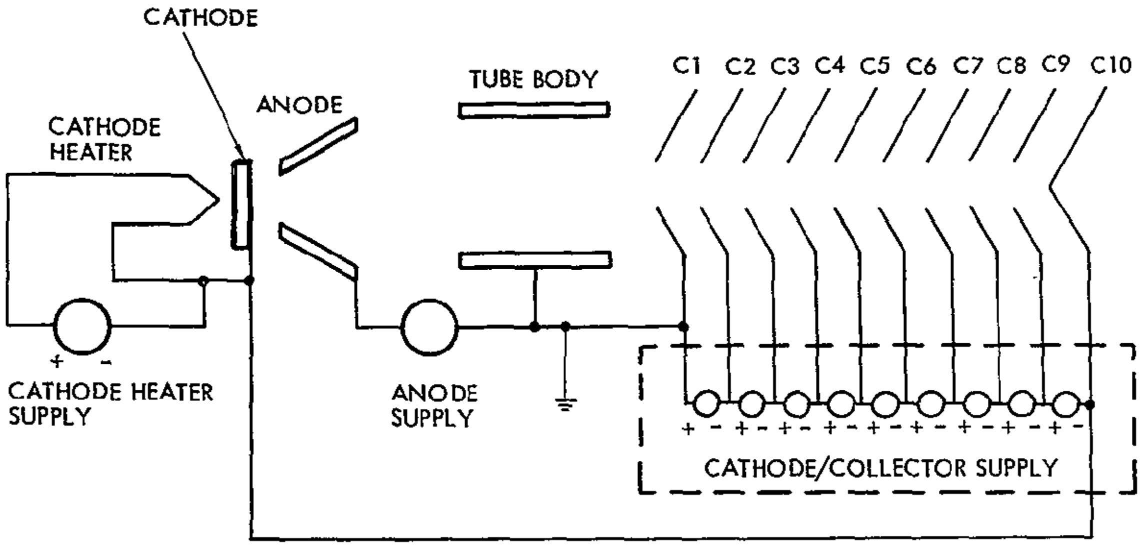


Figure 4-1. Connection of Major PPS Output Supplies

The means of implementing protection for the OST in the event of output faults, primarily high voltage arcing, is readily accommodated in a common high voltage supply configuration. The probability of high voltage arcing, though low, is such that gun area arcs (cathode to anode, cathode to body) are more likely to occur than those in the collector region (collector to body, collector to adjacent collector). A sustained arc or short for all conditions, with the exception of collector-to-collector shorts, results in increased tube body current; therefore, protection can be simply afforded by turning off the high voltage supply when body current exceeds an acceptable current level. Generally, the energy required to sustain a high voltage arc is not available and an arc, accordingly, would extinguish. However, provision must be made to limit discharge energy to tube elements. Permanent shorts, such as those between adjacent collectors, although of very low probability, require that appropriate measures be taken to protect the power supply.

4.2.1 High Voltage Cathode/Collector Supply

Various candidate switching type dc-to-dc converter approaches were evaluated for implementation of the basic power circuit of the cathode/collector supply. Each circuit type was evaluated in terms of required power switching ratings, method of establishing required high voltage outputs, weight impact in the design of input and output filters and high voltage transformer, efficiency, circuit part count, steady-state and transient performance (especially under startup and output fault conditions), and control logic requirements for regulation and protection.

The candidate circuits can be categorized in terms of the two basic techniques for accomplishing the ac inversion function: parallel inversion and series inversion. In the former, as exemplified in the familiar chopper preregulator-squarewave inverter, the load, reflected to the primary of the inverter transformer, is essentially connected in parallel with the power source through the chopper power switch. During startup or overload conditions, parallel inversion schemes suffer in that high peak currents are drawn from the power source which can force the power switch to come out of saturation, resulting in high power loss and compromising reliability. Voltage collapse of a current-limited solar array source could result under these conditions in the TEP application.

In series inversion power circuit configuration, a passive energy storage element is connected in series with the power source, switch, and reflected load. The addition of this element acts to provide a current limiting function to the power stage, thus accomplishing control of current buildup during startup and overload conditions. The power source is protected from current surges and voltage collapse, and the power switch is relieved from overstress since transients are under design control.

In reviewing the circuit approaches for the cathode/collector supply, the single-ended series inductor energy storage converter (variously termed buck-boost, or flyback-type converter) appeared to be the most suitable candidate, having been applied previously in high voltage applications. However, in multiple output configurations, it suffers in comparison with circuits utilizing a conventional output transformer due to the poorer flux coupling of the former. As a result, the distribution of output voltages under widely changing load conditions is not as well controlled.

Another problem in applying this circuit in a high voltage, high power application is the limited availability of high voltage, fast switching power transistors. Those available would necessitate the use of several power stage sections to achieve the overall power capability required, with attendant penalties of added part count and weight.

In order to provide the most optimum and reliable configuration, an inverter scheme was developed* that embodies most of the desirable features characteristics of series inductor energy storage converters when used in high voltage, high power applications. This circuit, termed herein as a modified (current source) chopper preregulator/inverter, is illustrated in simplified form in Figure 4-2. Current and voltage waveforms in the key components are illustrated in Figure 4-3.

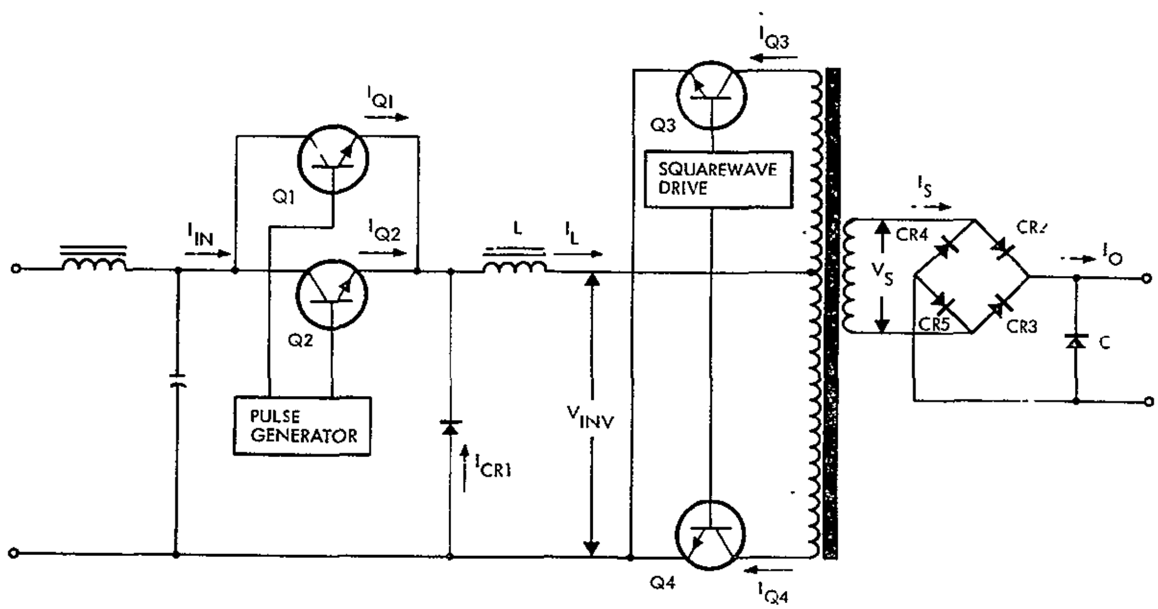


Figure 4-2. Current Source Chopper Preregulator/ Squarewave Inverter

*Originally developed by D.L. Cronin of TRW Systems

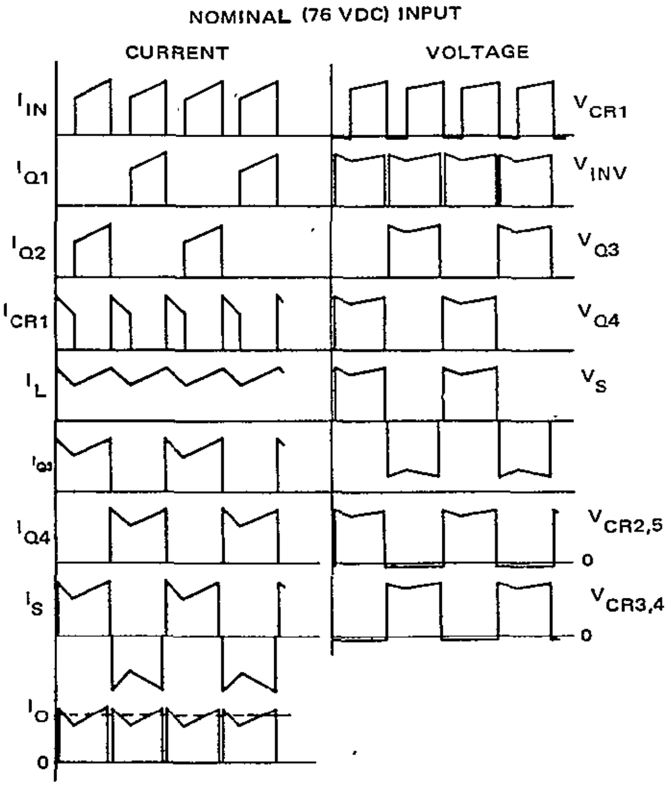


Figure 4-3. Typical Waveforms in Modified Chopper Preregulator/Inverter Power Circuit

Although appearing physically similar to the conventional preregulator/ squarewave inverter, the characteristics obtained in the new circuit eliminate all the basic disadvantages inherent in the conventional configuration. As noted previously, the conventional circuit reflects high peak currents back to the power switch during overload and startup conditions. The inverter power switches in a conventional inverter circuit experience high peak power stresses during output short or arcing conditions until action is established by an overload current sensor and control loop. Also, high transistor stresses are developed from transistor storage time effects and transformer saturation resulting from half-cycle volt-second unbalance.

In the new circuit, the voltage source character of the conventional configuration is altered to a current source by removing the chopper integrating filter capacitor, the function of which is provided by the total reflected output filter capacitance. By this expedient, the integrating filter inductor can limit the rate of rise in current under fault or start-up conditions, both in the chopper as well as in the inverter transistors, before corrective action is taken, thereby protecting the power switches. As with other series inductor energy storage converters, known and predictable current stresses are applied to the power switches, thus substantially minimizing derating requirements on these parts and avoiding the overdesign normally encountered. This is especially important in high voltage applications because of the inrush current drawn in charging up the relatively high interwinding capacitances associated with high voltage transformer designs. The overstresses resulting from transformer volt-second unbalance and transistor storage time effects are eliminated by conversion of the conventional circuit to one having series inductor converter characteristics. Note that in this configuration, one or both inverter transistors can be on, and the condition of both switches off must be avoided.

In comparing the selected circuit approach to another viable candidate, a push-pull series-inductor energy storage converter, an efficiency penalty is suffered in the former, in that power is handled in two switches rather than one. However, an efficiency of 90 percent for the basic power stage was attained, a value consistent with meeting the overall efficiency requirement for the PPS. Significant advantages are better distribution of output voltages with wide load variations due to the better flux coupling inherent in a conventional transformer over that obtainable in a gapped inductor/transformer. For the PPS this is especially important in that:

a) OST collector voltages are derived from a common output transformer and must be regulated to within ± 3 percent over a wide load range.

b) Although two power magnetics are required in the push-pull inductor energy storage converter and in the selected circuit, the latter yields lower weight since only one is a high voltage device, a major factor in that high voltage magnetics weight is largely governed by dielectric considerations rather than copper and core material weights.

c) Use of a chopper preregulator minimizes the maximum voltage stresses applied to the inverter power transistors simplifying the selection of space-qualified parts, a situation not afforded presently with the use of the push-pull series inductor circuit.

Other advantages accruing are small output filter requirements (and thereby low discharge energy in the event of arcs and fast output transient response), low output impedance, minimum control circuit complexity, and reduced output rectifier voltage stress (due to clamping of transformer ringing spikes by the output filter capacitor).

The basic PPS cathode/collector supply is shown in Figure 4-4. The power elements include the input line filter, chopper preregulator, inverter, and high voltage output section. The control logic functions are indicated in block form along with an active output filter in the ground or body line.

A two-stage passive input filter is used. The first stage, consisting of L1-C1-R1, controls resonant peaking of the filter. The second stage, L2-C2, supplies most of the pulse current demand of the switching preregulator. The ac component of the pulse filter output current is attenuated to the required input level by the combined action of both filter sections.

The chopper preregulator consists of power transistors Q1 and Q2 along with associated drive components, flyback diode D1, and series inductor L3. The transistors Q1 and Q2 are alternately driven so that a 100 percent duty cycle can be obtained while still maintaining an adequate period for reset of the respective drive transformers, T1 and T2. This allows the chopper output voltage to be maintained at the highest possible level to minimize inverter currents and high voltage transformer (T3) turns ratio. The commutating diode and series inductor serve the same function as in a conventional chopper. The rectifier filter capacitors at the output of the high voltage transformer, reflected to the primary, assume the chopper filter capacitor function.

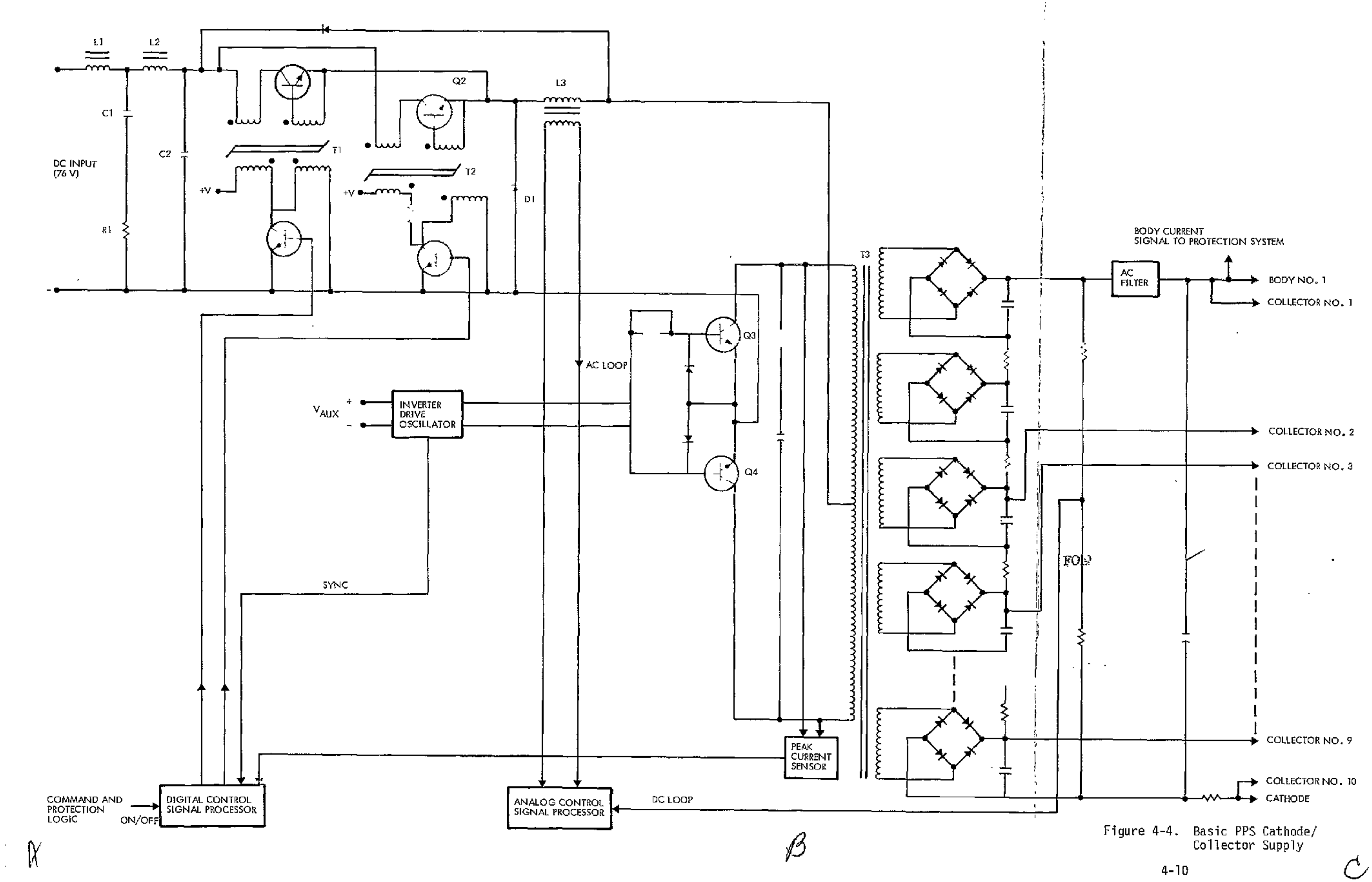


Figure 4-4. Basic PPS Cathode/
Collector Supply

The mmf continuity in inductor L3 is maintained by the conduction of inverter transistor Q3 and/or Q4. When both Q3 and Q4 conduct during the overlap time of the switchover, the current in all power transistors and the source is limited by L3. This prevents excessive power dissipation during switching, resulting in improved efficiency and reliability.

A current feedback control loop utilizing a peak current sensor in the inverter primary is utilized to provide a controlled limit on current through the power transistors. When a predetermined value of current is exceeded, a signal is generated to force the immediate turn-off of the power circuit. Incorporating these features (current feedback and current limit inductor) in the power circuit design results in controlled current stress in the critical parts under all operating conditions, including startup, overload, intermittent arcing, or any combination of single or multiple terminal output shorts. This approach (in conjunction with careful design of the high voltage power transformer) greatly enhances the reliability of the PPS.

The required voltages for the cathode and multistage collectors are derived from the series-connected rectifier/filter outputs on individual secondary windings of T3. Each of ten identical secondaries (1.13 kV) is interconnected through current limiting resistors whitch limit output filter capacitor stresses during possible tube arcing conditions as well as controlling the maximum energy discharge into tube elements. In addition, these resistors prevent excessive voltage buildup in the output power return line during tube arcing.

A ripple attenuator or active filter, designed for 40 dB attenuation in the low audio range, is provided in the high voltage cathod-to-body output to meet the stringent 0.01 percent pk-pk ripple requirement. The active filter supplements the line noise rejection provided by the two-loop voltage regulator. Sensing of the cathode-to-body output voltage for regulation is accomplished before the active filter, and the latter is designed to present a variable ac but constant dc drop across the active filter series transistor.

The control logic section of the cathode/collector supply utilizes an advanced standardized two-loop voltage regulation system. This type of control provides excellent static and dynamic regulation characteristics, low output impedance, good stability, and good line noise rejection characteristics. The cathode-to-body voltage signal, derived from a high impedance divider, is OR-gated into an impedance matching amplifier within the analog control signal processor (ACSP). The output of this amplifier is used as the dc input signal for an integrating amplifier stage. The ac signal of the second loop, which reestablishes chopper duty cycle corrections within a half cycle of the switching operation, is derived from a winding on the chopper inductor, L3, and fed differentially into the integrating amplifier stage. The integrator output is used to control a threshold detector and a digital control signal processor (DCSP) which provides the proper signals for the base drive of transistors Q1 and Q2. The pulsewdith modulation of the chopper transistors is slaved to the inverter frequency which is established by the oscillator of the internal power supply. A synchronization circuit in the DCSP is used for this purpose and ensures the sequential switching operation of Q1 and Q2 within the same constant frequency cycle.

An undervoltage on the main bus (76 volts) is detected in the ACSP integrator stage which clamps the chopper driver transistor off when the cathode-to-body voltage drops out of the regulation band for longer than approximately 0.4 second. Undervoltage on the housekeeping (27.5 Vdc) bus is sensed directly and, along with excess body current and MDC pressure signals, acts via the protection logic to effect an off command (MDC pressure is monitored by sensing ion pump supply current). As noted previously, all shorts or arcs between tube elements are seen in increased body current with the exception of collector-to-collector shorts. In this event, protection is obtained via the integrator stage which senses the resulting out-of-regulation condition.

4.2.2 Grounding and Isolation

The grounding and isolation concept selected for use in the PPS is predicated on the containment of interference, generated in the unlikely event of a high voltage arc, so that harmful transients are not propagated into PPS low voltage components or into other spacecraft systems. To attain this end, input and output isolation is maintained as well as isolation and separate returns of the command and telemetry systems. Input and signal returns can be tied at a common point in the spacecraft structure. All PPS returns are floating with respect to the case, and the output return is connected to the TWT structure. Electrostatic shields are used in the high voltage transformers (cathode/collector and cathode heater supplies), and capacitors are connected between input dc returns and the PPS case. This maintains input circuitry at PPS structure ground under any transient (arc) condition in the OST or its interface with the PPS.

4.3 ELECTRICAL DESIGN

Brief functional descriptions of the various circuits and supplies comprising the PPS are presented in the following subsection, followed by a discussion identifying the specialized electrical components used in the PPS design. For the latter, primarily high voltage components, the program utilized in the evaluation and testing of nonstandard components is briefly described. The concluding subsection presents highlights of the overall PPS high voltage design.

4.3.1 Circuit Descriptions

For the following circuit descriptions, refer to the appropriate sheet of Figure 4-5, the PPS schematic diagram (12 sheets, Schematic No. 274652).

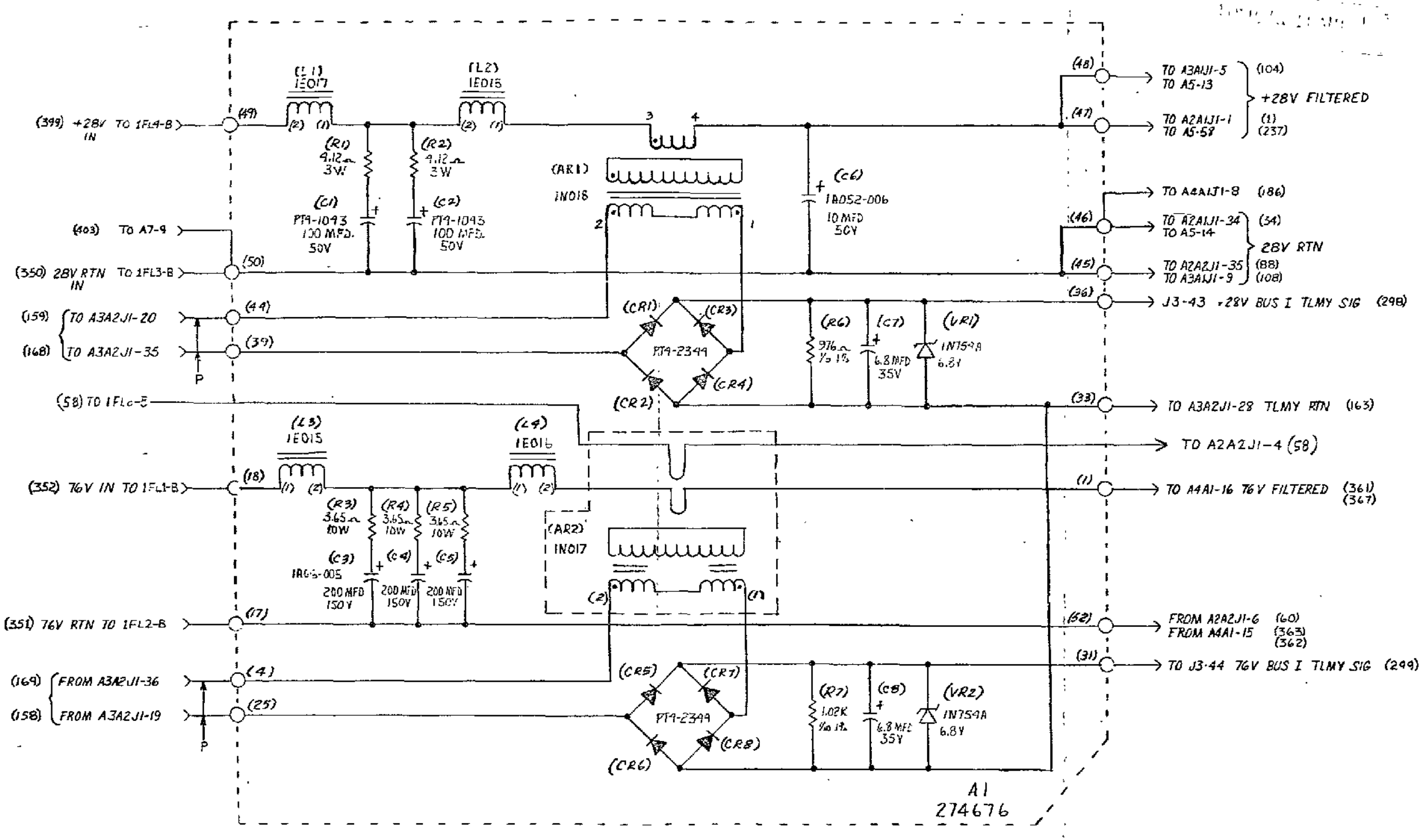
4.3.1.1 Input Power Line Filters (Figure 4-5 Sheet 2)

The input power line filters for both the experiment and housekeeping buses are shown on sheet 2 of Figure 4-5. Both are passive two section L-C filters which are designed to the EMC requirements as set forth in Section 3.1.1-4. The specific design constraints are:

- Source current ripple per MIL-STD-461A, Notice 3
- The 2.0 volt rms audio frequency input at nominal line voltage
- Input voltage transient susceptibility.

From these constraints, the filters must provide not only high attenuation at the PPS switching frequencies but must also exhibit sufficient damping to the input audio frequency line voltage disturbances so that filter resonant peaking is properly controlled at the filter output. In addition, the filter inductors must not saturate in the presence of input line voltage transients.

The two-section filter design provides high performance in reducing conducted interference, controlled resonant peaking, limited inrush current at startup, and very low loss. With these features, very little size and weight penalties are incurred when compared to a conventional single section L-C filter design offering only partial performance at corresponding levels.

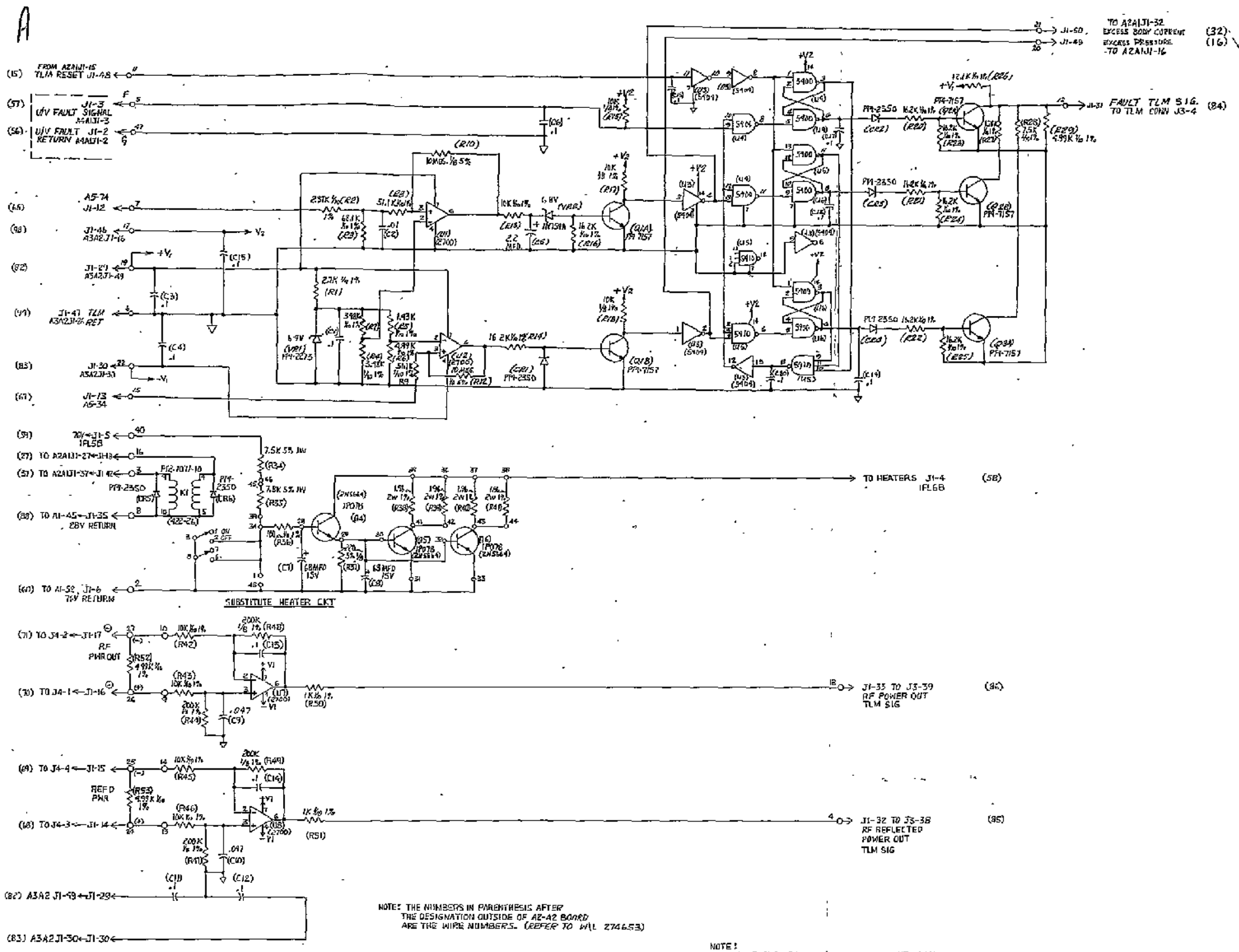


NOTE: THE NUMBERS IN PARENTHESIS AFTER THE DESIGNATION OUTSIDE OF A1 BOARD ARE THE WIRE NUMBERS. (REFER TO W\L 274653)

Figure 4-5. Power Processor System Schematic Sheet (2 of 12)

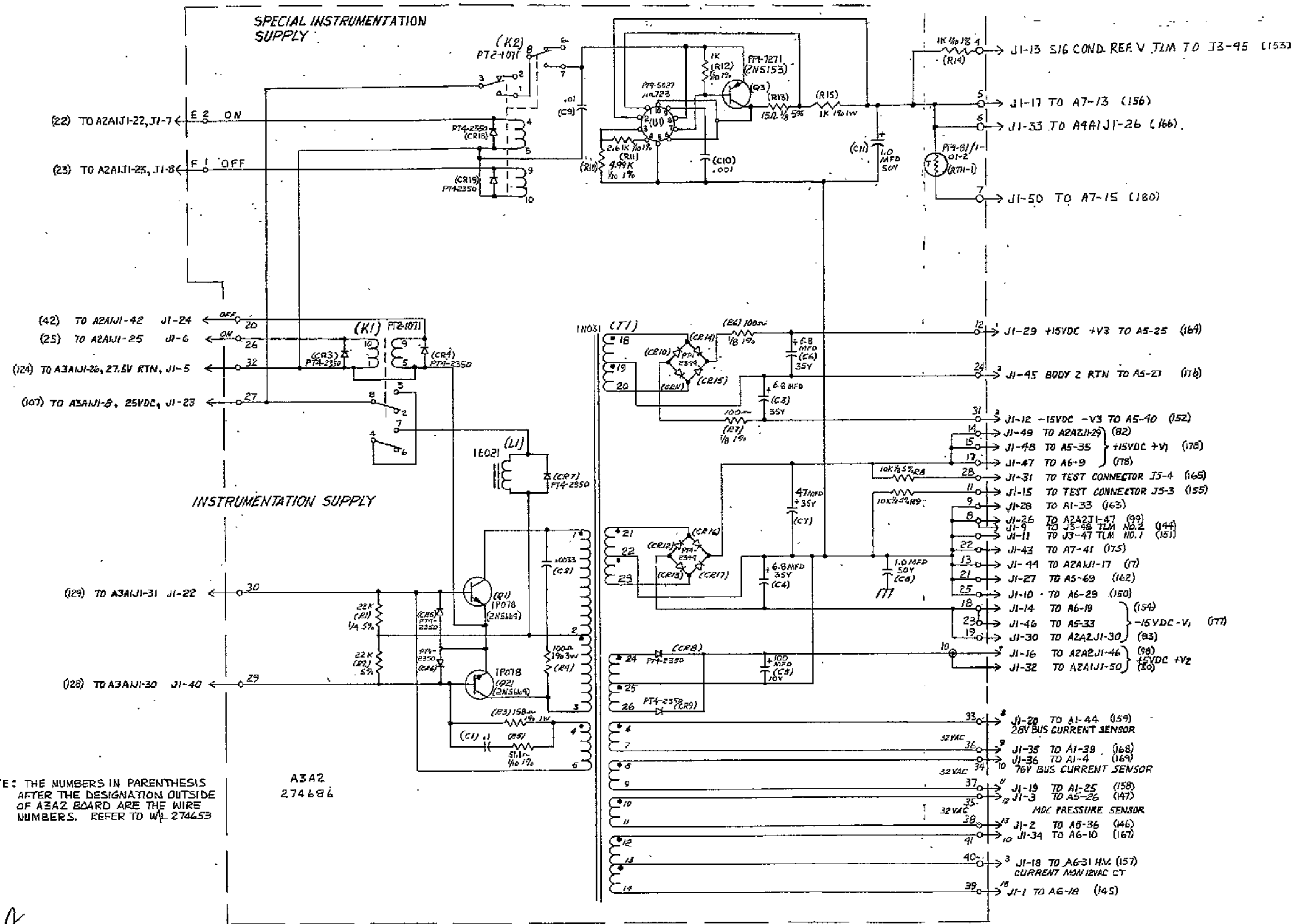
B

A



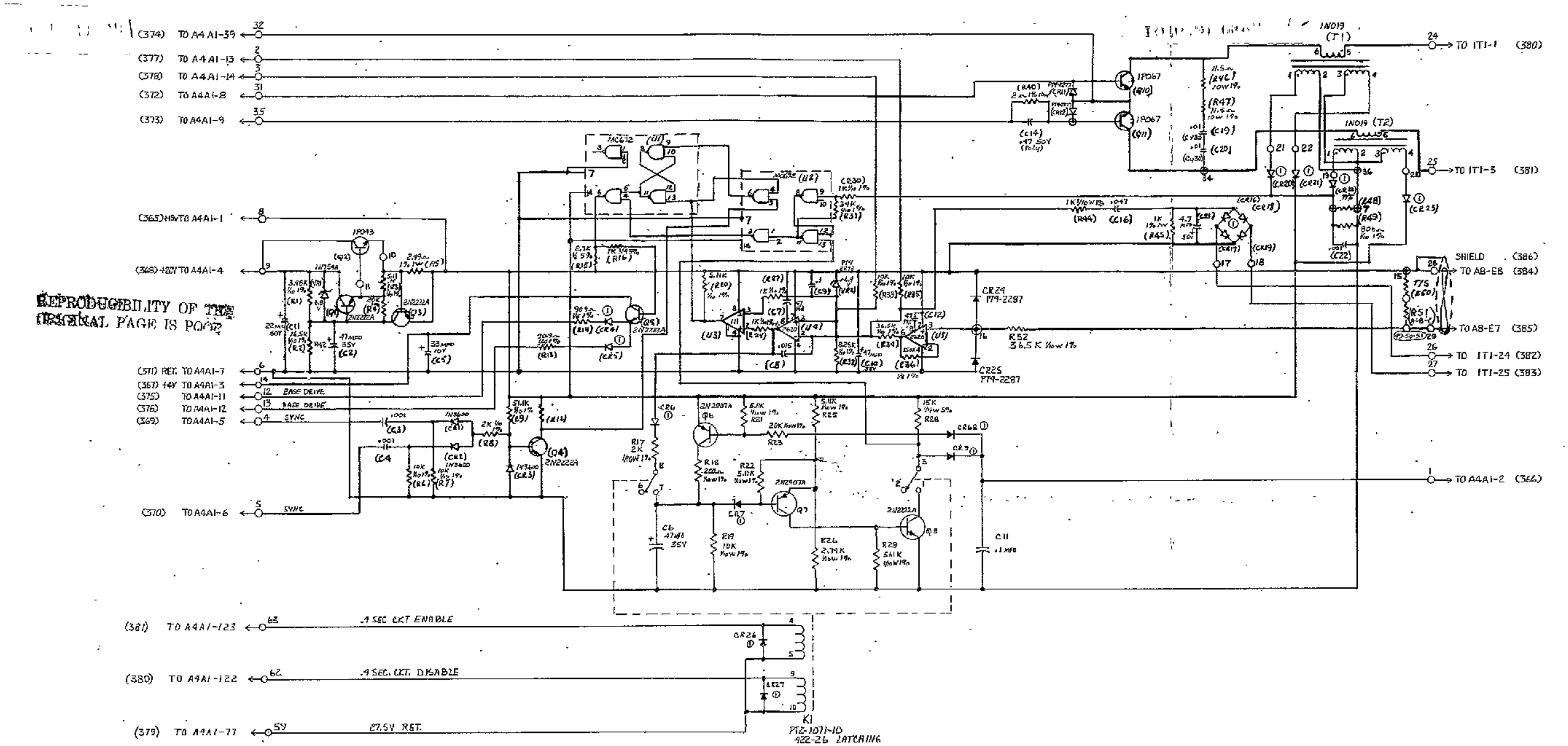
NOTE:
1. VOLTAGES DERIVED FROM INSTRUMENTATION SUPPLY
AREAS AS FOLLOWS:
±V1 ±15VDC OUTPUTS 4-5-6 REF
+V2 +5VDC 7-5 TLM RTN
2. ▽ DENOTES TLM RTN

Figure 4-5. Power Processor System Schematic Sheet (4 of 12)



NOTE: THE NUMBERS IN PARENTHESIS AFTER THE DESIGNATION OUTSIDE OF A3A2 BOARD ARE THE WIRE NUMBERS. REFER TO WL 274653

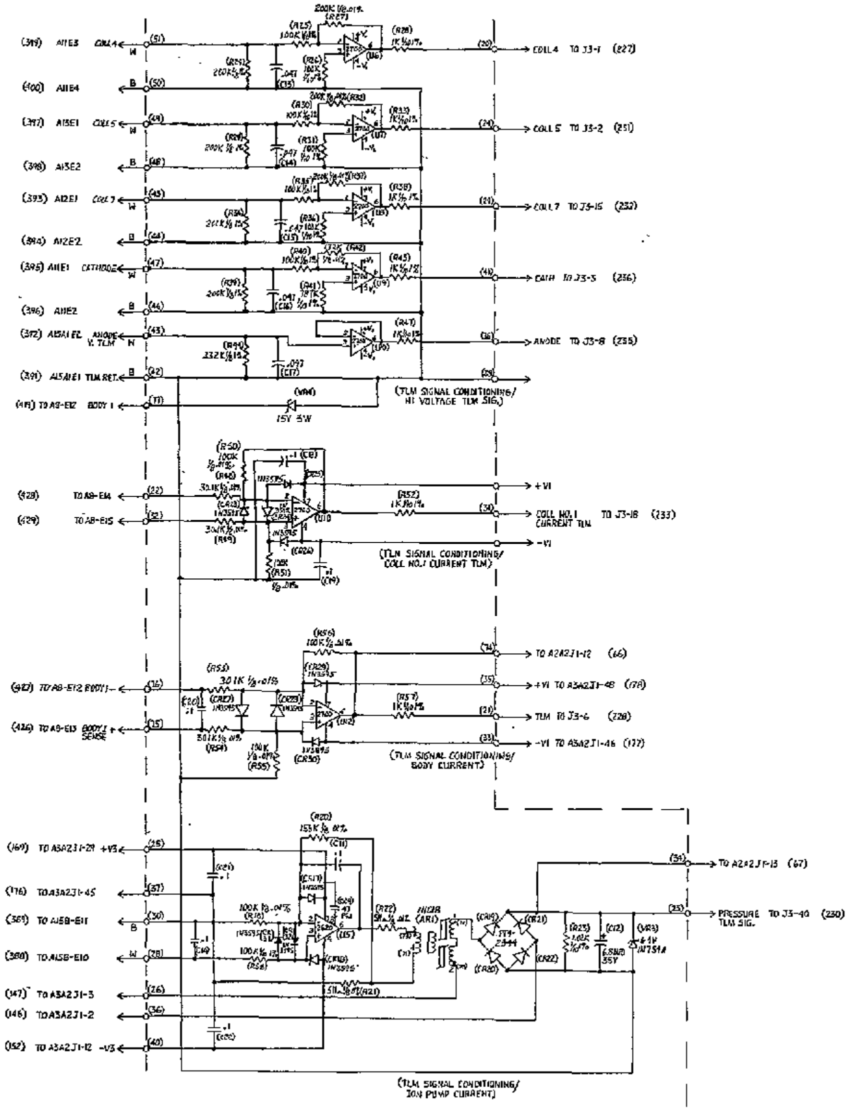
Figure 4-5 Power Processor System Schematic Sheet (6 of 12)



NOTES: UNLESS OTHERWISE SPECIFIED

1. ALL DIODES CR4 THRU CR9, CR16 THRU CR23, CR26, CR27 ARE PT9-2350.
2. ALL CAPACITORS IN MFD.

Figure 4-5. Power Processor System Schematic Sheet (8 of 12)



NOTES, UNLESS OTHERWISE SPECIFIED
1. ALL CAPACITORS ARE MFD

±V1 ±15VDC OUTPUT 4-5-6 REF TO TLM RET.
±V3 ±15VDC OUTPUT 1-2-3 REF TO BODY 1
∀ DENOTES TLM RTN.

A

NOTE: THE NUMBERS IN PARENTHESIS AFTER THE DESIGNATION OUTSIDE OF BOARD ARE THE WIRE NUMBERS. (REFER TO W/L 274653)

Figure 4-5. Power Processor System Schematic Sheet (10 of 12)

B

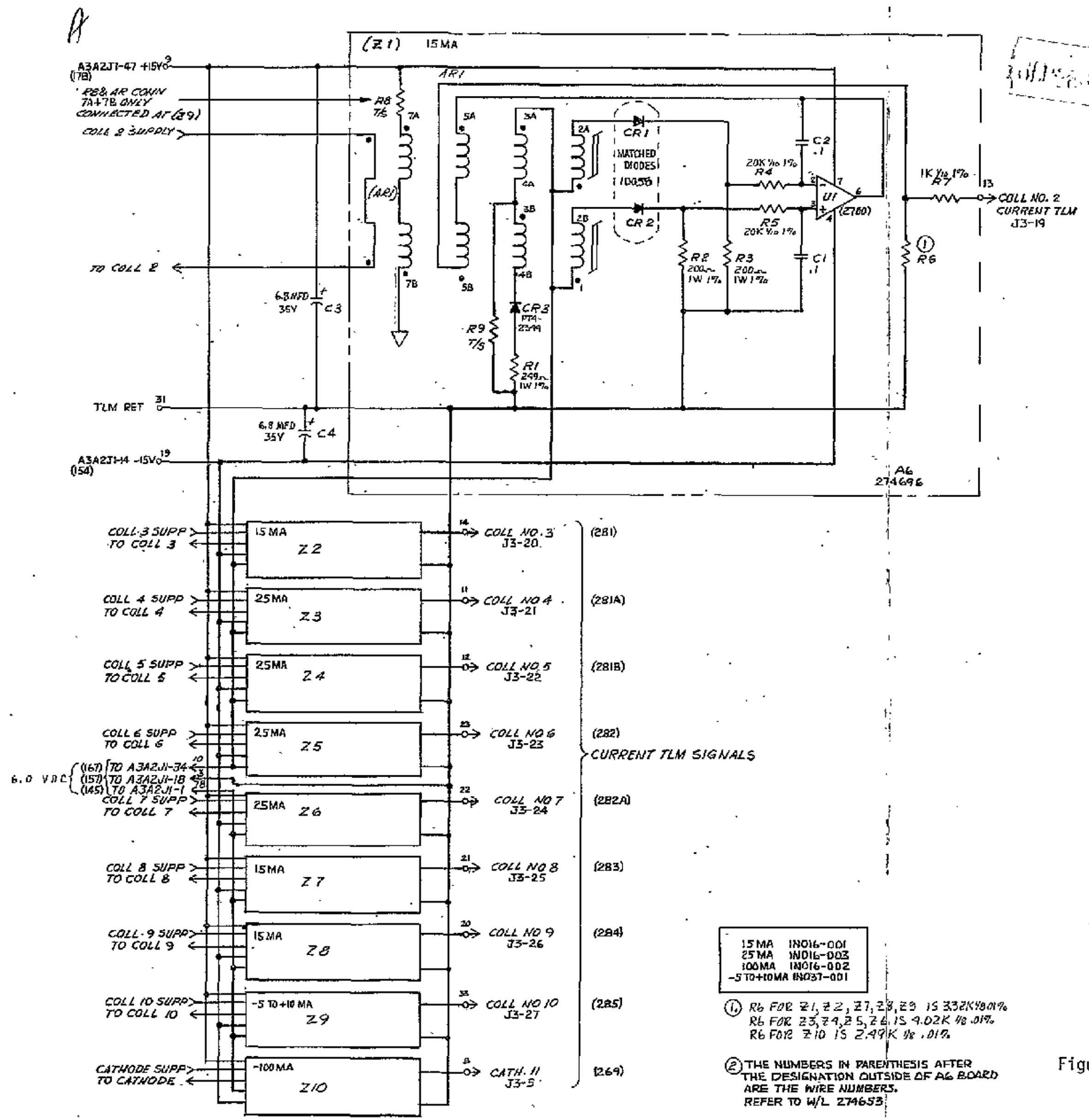


Figure 4-5. Power Processor System Schematic Sheet (11 of 12)

For the experimental bus, the input filter consists of first section L3-R3, R4, R5-C3, C5, second section L4-C2 (C2 of sheet 7), and for the housekeeping input, first section L1-R1, R2-C1, C2 and second section L2-C6. The first section controls the magnitude of the resonant peaking at the filter output. The second section supplies most of the pulse current demanded by downstream switching regulators. The alternating component of the pulse current, as seen at the input, is attenuated to below the required level by the combined action of both filter sections. Measured conducted ripple currents on both buses are 6 and 15 mA peak, respectively, for the 76 and 27.5 volt lines, yielding respective margins of 12 and 11 dB below specified MIL-STD-461A, Notice 3 levels.

Resonant peaking values of both filters are below 3 dB, and the 76 volt bus filter output sees less than a 1 volt change when subjected to 100 volt, 10 μsec input line transient.

4.3.1.2 Cathode/Collector Supply (Figure 4-5, Sheets 7, 9, and 12)

The following discussion supplements the introductory description presented for this supply in Section 4.2.1.

A simple block diagram of the cathode-collector supply is shown in Figure 4-6. It is basically a chopper preregulator, parallel inverter configuration employing the two loop analog signal to discrete time interval converter (ASDTIC) control system, where high dc gain can be obtained simultaneously with good regulator stability. The two loops are: conventional dc control loop I and ac loop II sensing the integrator inductor voltage. The ac and dc information is summed and continuously integrated by an operational amplifier producing a ramp output, which is superimposed on the dc error to effect duty cycle control of the power switch through a threshold detector and a pulse generator. The additional blocks shown are for protection, command, and power interfaces.

The chopper preregulator is shown on sheet 7 of Figure 4-5. It consists of push-pull power switching transistors Q2,Q4 and associated driver stages, chopper inductor L3, and commutating diode CR25. Also shown is the isolation transformer T1 supplying, in part, the preregulator drive power requirements. Sheet 8 illustrates the inverter stage, including power switching transistors Q10,Q11, peak current sensors T1,T2 with associated processors U1,U2, and the feedback control logic section. This is made up of a unity gain impedance matching amplifier U5, matching the impedance of the high output voltage divider resistor (R50,51), and the integrator and threshold detector stages (U4,U3). The combined action of integrated circuits U1-U5 act to control transistor Q5, which, in turn, provides the requisite duty cycled base drive signals to the chopper preregulator driver stage.

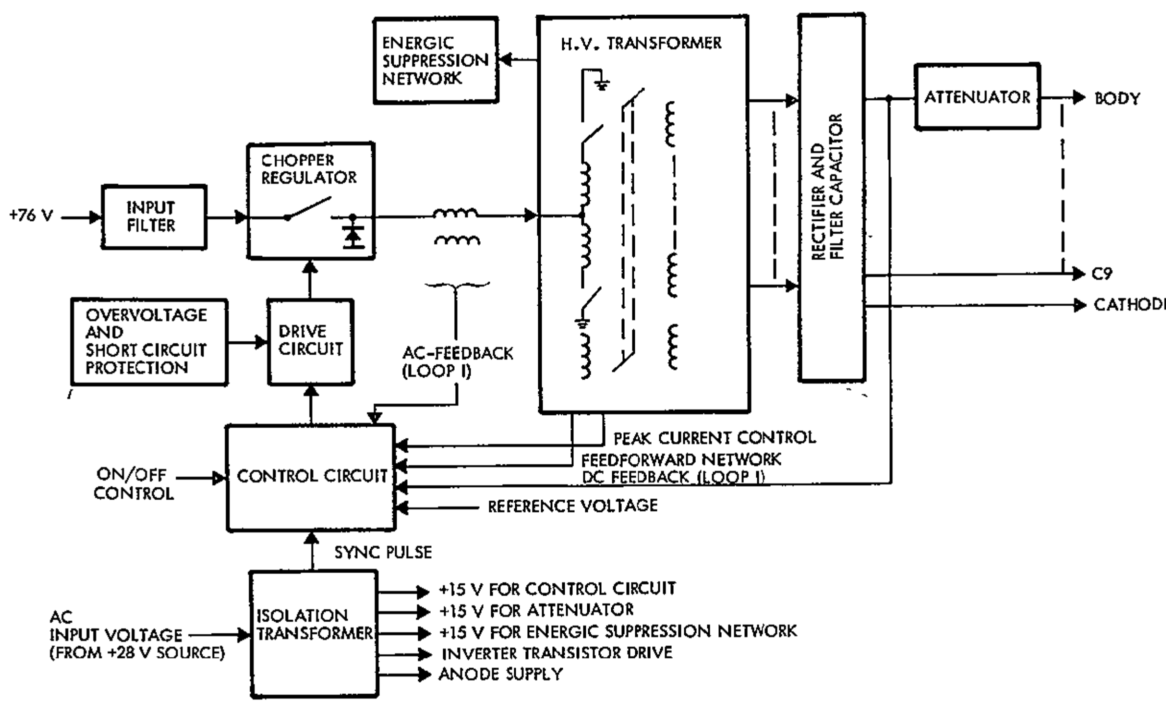


Figure 4-6. Block Diagram of Cathode-Collector Supply

The synchronization circuit is used to slave the chopper preregulator switching frequency to that of the inverter is established in the Q4-CR1, CR2 circuit. A minor loop rate feedback signal is derived from the output high voltage transformer via diode bridge CR16-19 and R44-C16 to the integrator (U4) input. The use of high noise immunity logic components, U1,U2 simplifies the circuit required to perform the required function as well as providing good noise immunity.

Transformer T1 (sheet 7) supplies the following outputs:

- Supply voltage for high voltage output attenuator-winding 13-14-15
- Chopper preregulator drive power and feedback control logic power-winding 16-17-18
- Preregulator synchronizing voltage-winding 19-20-21
- Anode supply power-winding 8-9-10
- Inverter drive power-winding 3-4.

Regulator Q1,Q2,Q3 (sheet 8) provides regulated +15 volt power primarily to the feedback control logic section of the cathode/collector supply and was required to provide the desired degree of rejection to audio noise on the housekeeping bus.

4.3.1.2.1 Cathode/Collector Supply Protection. The circuitry made up of relay K1 and transistors Q6, Q7, Q8 (sheet 8) acts to disable the cathode/collector supply should a long-term output overload occur. Because of the selected protection circuit implementation, an undervoltage on the 76 volt bus also results in supply shutdown. Either of these conditions must exist for approximately 0.4 second (set by C6, R19) for shutdown to be effected. For 76 volt bus undervoltages or output overloads lasting less than 0.4 second, no undue component stress occurs and the cathode/collector supply automatically resumes normal operation following the abnormal line and/or load condition.

This protection feature, designated "high voltage" protection, can be enabled or disabled by command via relay K1. The input to the protection circuit is derived via CR6, from the output of the integrator stage (U4) of the feedback control logic section. With the protection circuit enabled for the supply operating normally, Q6,Q7,Q8 are off. The collector of Q8 is coupled, via diode CR9 to the common connection of diodes CR20 and CR21 (sheet 7) in the chopper preregulator driver stage and to pin 13 of the peak current sensor (threshold detector) gate, U2 (sheet 8). The output of integrator stage U4 (approximately 8 volts) maintains a charge of approximately 7 volts on capacitor C6 in normal operation.

Assuming an abnormal 76 volt line undervoltage or overload condition, the integrator (U4) output drops to 2 volts of less and C6 begins to discharge through R19. In approximately 0.4 second, the voltage across R19 has dropped an amount sufficient to cause conduction of Q7, thereby Q8. With Q8 turned on, threshold detector U2 acts in a manner similar to that when receiving a signal from the peak current sensor, shutting off the chopper preregulator via transistor Q5. Since the preregulator is now off, an effective self-latching results (Q7 and Q8 remain "on") and the supply remains off.

Upon removal of the abnormal line or load condition, the supply must be reset and this is accomplished by sending a cathode/collector "off" command followed by an "on" command. Referring to sheet 7, the off command applies ground return, via contacts (6 and 8) of relay K1 to both the common connection of preregulator diodes CR20 and 21 (clamping off the preregulator), and to the common connection of diodes CR9 and 68 (sheet 8). In the latter, CR68 is now biased on, allowing Q6 to conduct which in turn recharges capacitor C6 in excess of 12 volts. This action turns Q7 and Q8 off, permitting a subsequent normal restart with sufficient delay time to allow high voltage output filter capacitor charging.

For abnormal line/load conditions existing for less than 0.4 second, the discharge time of C6/R19 is not of sufficient duration to cause turn-on of Q7 and Q8, and the supply outputs are out of tolerance for this brief period. As indicated previously, no component overstress occurs in this condition.

Protection is also provided against undervoltage on the housekeeping bus. This protection is required because this source provides in part, the logic power in the cathode/collector supply and undervoltage would cause loss of power transistor peak current control and consequent overstress.

The output of the 25 volt preregulator (sheet 5) is sensed via the VR2, Q6 circuit shown in sheet 7. Referring to the latter, a normal 25 volt present breaks down zener diode VR2, forward biasing Q6. When a cathode/collector off command is sent, the coil of nonlatching relay K2 can then be initially energized. Once energized, it remains so via its own contacts, which are connected to the 25 volt source. A cathode/collector on command then starts normal operation. The input side of optical coupler Q5 is connected in series with the Q6 collector and is used to provide a ground isolated signal for undervoltage to the fault telemetry circuit (sheet 4).

When an undervoltage occurs at the 25 volt input, then VR2 and Q6 open, deactivating K2, whose contacts 8,6 connect ground to the common connnection of diodes CR20,21 in the chopper preregulator, shutting off the cathode/collector supply.

4.3.1.2.2 Cathode/Collector High Voltage Outputs (Figure 4-5, sheet 12). The cathode/collector high voltage output circuitry is shown on sheet 12 along with the anode and ion pump supplies, cathode heater supply output components, and high voltage output telemetry dividers.

The high voltage inverter transformer, T1, utilizes ten series connected, individually filtered bridge rectifiers to develop the full cathode-body voltage, with intermediate taps brought out to supply the various collector voltages. Resistors R51 through R59, interconnecting the individual bridge rectifier outputs, and resistors R109, R110, and R72, provide current limiting in the event arcing occurs between any two points in the cathode/collector output circuitry. This protection serves to limit both energy dissipated in OST elements during arc discharges and peak discharge currents which otherwise would overstress output components.

High voltage filter capacitors are connected across the total secondary output (C35) before the attenuator circuit (U5, Q16, and associated components) and downstream from the attenuator (C41).

The cathode-to-body voltage is sensed across the total secondary output via high voltage divider resistors R62, R60, and R94. The voltage feedback signal is developed across R60 (in parallel with R50, R51, sheet 8).

The attenuator circuit provides a filtered 11.3 K Vdc output voltage with a total ripple of less than 0.01 percent of the dc output. It is accomplished by presenting a variable ac voltage drop in series with the cathode-to-body voltage source. The circuit used is basically an active lowpass filter with a rolloff frequency determined by R64 and C36 ($\sim$0.3 Hz). It can reject approximately $\pm$50 volts of ac ripple present at the input.

Operational amplifier U5 is connected in a unity gain configuration with the reference voltage provided by the sum of zener diode VR4 through VR10 voltage drops, filtered by R64 and C36. It drives transistor Q16 which, in conjunction with series components R68,R69, and VR25, presents a constant dc drop of approximately 50 volts with respect to body potential.

4.3.1.3 Cathode Heater Supply (Figure 4-5, Sheet 9)

The cathode heater supply must provide a well regulated, low ripple dc current output to the OST cathode heater. Also, provision must be made to vary cathode heater supply output power in steps by command, the steps corresponding to 0, 50, 100, 110, and 120 percent of nominal full rated power. The low voltage output of the heater supply is referenced at cathode potential (-11.3 kV dc). Detailed requirements are:

Output current regulation	$\pm$1% (over 100-120% load)
Output current ripple	2% pk-pk
Output voltage (nominal)	4.2 Vdc (-11.3 kV to ground)
Load range	7.06 w max (120%) 2.94 w min (50%)
Output current limit	1.5 amps

The regulated spacecraft housekeeping bus (27.5 Vdc) must be used for the input power source so that the TWT cathode heater can be powered (at the half power condition) during eclipse periods when the high power experimental bus (76 Vdc) is inactive. This eliminates a potential problem in cathode heater life (due to excessive thermal cycling and contamination) that would arise from powering the heater supply from the high power bus.

The selected circuit configuration consists of a regulated inductor energy storage type, dc-dc converter. This circuit provides the regulated output requirement at high efficiency with a low part count.

Referring to the cathode heater supply schematic (sheet 9 of Figure 4-5), the basic converter circuit consists of power switching transistor Q3, inductor/transformer T2, diode CR4, and output filter C4-C7,L2,C15. Input energy is provided via the housekeeping bus input filter and stored in T2 during the on-time of transistor Q3. When Q3 is turned off, energy stored in T2 is delivered from the secondary winding to the cathode heater and output filter through fast recovery diode CR4. Output control is achieved by adjustment of the on/off ratio. Current in the secondary winding is sensed (via current transformer T3) and compared with a reference (VR2) in integrator amplifier U4. The two-loop control concept is also utilized in this supply, the second loop being derived from an ac voltage on the secondary of T2 (winding 9-10).

The output of U4 in conjunction with a threshold level built into integrated circuit U3, actuates a pulse generator, made up of pulse stretcher U1 and flip-flop U2. Integrated circuit U1 is effectively a clock which sets the initial on/off ratio of Q3. The lower section of U1 is connected to the input supply voltage (via R2) and adjusts on-time to provide a measure of direct line compensation. The output current to the heater load is regulated by controlling the off time of Q3 via integrator amplifier U4, threshold detector U3, and the upper section of U1. Flip-flop U2 is used to provide the variable duty cycle signals to the Q3 driver stage, consisting of Q2, T1, and associated components. Proportional current drive is used for Q3 to optimize supply efficiency.

A regulator, made up of Q1, VR1, and associated components, provides the initial startup voltage (+15 volts) when the "cathode heater 50 percent power" command is sent. This command connects the start regulator output to the driver stage and feedback controls via contacts 8 and 7 of relay K1. Conversely, the off command disables the supply by shorting out winding 5-6 of drive transformer T1. When the heater supply builds up, an internal dc voltage is developed via winding 5-6 of T2 and diode CR4. This voltage back-biases the startup regulator and supplies all internal voltage requirements.

In the 50 percent power condition, the heater supply output is set by the resistive divider (R16,R10) at the input of integrator amplifier U4, R16 being the load on output current sensing transformer T3. The 100, 110, and 120 percent heater power commands, operating respectively relays K3, K4, and K5, adjust the resistive divider ratio and, hence, the supply output power.

The required interlocks with regard to cathod heater control (Section 3.1.1.6) are:

a) With 50 percent heater power, the cathode/collector supply cannot be activated (the cathode/collector supply can be activated with heater supply at 0, 100, 110, 120 percent power).

b) The cathode/collector supply automatically turns off if the heater supply is commanded to 0 or 50 percent power.

c) The experimental bus fault clearing relay can only be activated when the heater supply is at 50 percent power, i.e., with the cathode/collector supply off.

Implementation for these interlocks is accomplished as follows. With the heater supply off, the relay contacts K1,K2,K3 are in the position shown in sheet 9, corresponding to the heater off state. In this state, relay K1 contacts 7,8 short out the driver stage transfomer T1, and contacts 3,2 disconnect 25 volts (derived from the housekeeping bus preregulator) from command logic relay drivers (sheet 3) used to enable heater supply full power adjust relays (K3,K4,K5). Also, relay K2 contacts 3,2 connect 27.5 volts from the housekeeping bus to the command logic section to allow cathode/collector supply turn-on with zero heater power.

When the 50 percent heater power command is sent, energizing simultaneously K1 and K2, the following conditions exist:

a) Heater supply driver stage is enabled.

b) 25 Vdc interlock signal is fed to the command logic section, enabling a subsequent processing of heater full power commands.

c) Cathode/collector supply is disabled.

d) 27.5 Vdc is supplied via contacts 8,7 of K2 and contacts 3,2 of K3 to the command logic section (fault clearing interlock). This permits processing of fault clearing relay open/close commands (make/break under zero power).

Upon sending a heater 100 percent power command, the cathode/collector supply is enabled by virtue of the 27.5 Vdc supplied through contacts 8,7 of K2 and contacts 3,1 of K3 to the command logic section. The fault-clearing interlock connection is also broken (contacts 3,2 of K3) preventing operation of the fault clearing relay.

4.3.1.4 Anode Supply (Figure 4-5, sheet 12)

The anode supply must provide a well regulated, adjustable dc voltage to the OST anode. Requirements are:

Nominal output voltage	+350 Vdc
Adjustment range	+150 to +550 Vdc
Load current	0 to 0.1 mA
Voltage regulation	$\pm$1%
Ripple	0.5% pk-pk

A simple dissipative regulator approach is utilized implementing the anode supply. Input power in rectangular-wave ac form is derived from a center-tapped winding on transformer T1 (sheet 7). As shown, the source ac is passed through current limiting resistors (R6,R7) to the supply proper (sheet 12). The ac is passed through rectifiers CR4,5 to transformer/rectifier T1,CR7-10 which develops the required level of anode voltage. Output filter capacitor C3 (in series with current limiting resistances R17,R18) provides the degree of required filtering. The anode voltage is sensed via a resistive divider and compared to a reference in error amplifier stage U1 (and associated components). The amplified error signal controls the voltage drop across transistor Q1, connected in series with the T1 primary center tap. For a given amplitude of input ac voltage, the drop across Q1 controls the magnitude of the applied T1 primary voltage and, hence, the output voltage. The wide adjustment range for output voltage is required so that the anode supply can provide the optimum setting for any individual OST.

Diodes CR5,CR6, connected across the anode supply output, provide a discharge path for energy stored in the output capacitors of the cathode/collector supply in the event of a cathode-anode arc.

4.3.1.5 Ion Pump Supply (Figure 4-5, sheet 12)

The ion pump supply, powering two pumps, must provide the following output characteristics:

Nominal output voltage	+3.3 kV dc (at 10 μA per pump)
Load current range	0 to 50 μA
Regulation (voltage)	$\pm$10%
Ripple	10% pk-pk

An ac output from the internal supply (sheet 5, winding 14-15-16) is the source for the ion pump supply proper. The rectangular ac waveform so derived is passed through current limiting resistors R30,31 (sheet 5) to the transformer T1 eight-stage voltage multiplier (sheet 12), used to develop the output requirements. A multiplier configuration is used because of the low power and modest regulation requirements of this supply. It offers the advantages of high voltage capability, low transformer output voltage, controlled parts stress levels, and low parts count.

The dc output of the supply is fed through separate current limiting resistors R1 and R100 to the individual ion pumps. Supply return current is sensed across resistor R3 for use in protection logic and telemetry signal conditioning circuitry.

4.3.1.6 <u>+25 Vdc Series Preregulator (Figure 4-5, Sheet 5)</u>

The preregulator provides a regulated +25 Vdc to the:

- Internal supply
- Instrumentation supply
- Special instrumentation supply
- Command logic
- Cathode/collector undervoltage circuit.

Total power rating is approximately 25 watts peak.

The regulator receives input power from the filtered housekeeping bus. A current-limited output is provided by means of current sensing resistor R12 and transistor Q2. The reference voltage for the regulator is established by the temperature-compensated zener diode VR1. Differential amplifier Q1 compares the output voltage (divider R5,R8,R10) with the reference voltage and provides the necessary loop gain to maintain good regulation. Frequency compensation of the regulator loop is accomplished with the R-C network C1-R7. Drive power for the series pass transistor (Q4) is provided from the +27.5 volt supply through a 6 Vdc output rectifier on the internal supply (winding 9-10-11 of T1).

Bypass of pass transistor Q4 can be accomplished by commanding relay K1 on (contacts 4,7). This nonlatching relay is then held energized via contacts 8,3.

4.3.1.7 Internal Supply (Figure 4-5, Sheet 5)

Basically, this supply provides a constant frequency clock used in the cathode/collector supply and current monitor circuits. The input power is supplied from the +25 volt series regulator.

The parallel inverter consisting of transistor Q7,Q8 and transformer T2 provides:

- AC drive for the cathode/collector supply (8.5 watts)
- +5 volts for the command logic (0.55 watts)
- Synchronization pulses for the instrumentation supply
- Drive power for the series regulator (0.6 watt).

The frequency of the parallel inverter is synchronized to the clock oscillator as soon as sufficient output voltage is available on the output of the series voltage regulator U1. Synchronization is done with the RC network R15, C5.

The constant frequency (10 kHz ±2 percent) of the clock oscillator (transformer T1 and transistor Q5 and Q6) is achieved by using a timing inductor L3, a constant input voltage provided by the μA 723 (U1) voltage regulator, and the temperature compensation inductor L1.

This supply is operated when the PPS enable command is sent, operating relay K2, the contacts of which apply 25 Vdc power to the inverter primary.

4.3.1.8 Instrumentation Supply (Figure 4-5, Sheet 6)

This supply is a parallel inverter receiving the input power from the +25 volt regulator and provides ac and dc power to:

- ±15 and +5 Vdc for the protection circuit, HV telemetry signal conditioning circuits, and pressure sensor (1.5 watt)
- 32 Vac to the MDC pressure sensor (0.2 watt)
- 12 Vac CT to the high voltage current monitor circuits (0.75 watt)
- 32 Vac to the low voltage current monitor circuits (0.2 watt).

The inverter frequency is synchronized to the internal supply frequency through the RC network, R32, C13 (sheet 5).

This supply is turned on when the PPS enable command is sent and disabled when either PPS disable or "all instrumentation off" commands are sent. The commands operate relay K1 which connects/disconnects +25 Vdc power to the inverter primary.

4.3.1.9 Special Instrumentation Supply (Figure 4-5, Sheet 6)

The supply utilizes a μA 723 regulator U1 driving a series dissipative regulator transistor Q3. It provides a regulated +5 Vdc bus, called "signal conditioning reference voltage" for powering all TEP temperature sensing networks. The supply is energized via relay K2 which applies +25 Vdc input power when the "special instrumentation on" command is sent. The "all instrumentation off" command disables this relay.

4.3.1.10 Command Circuitry (Figure 4-5, Sheet 3)

Twenty commands and associated command logic circuits are provided to satisfy the TEP system control and protection functions. Each command line is activated by a 5 volt, 50 msec duration pulse with a 20 mA source capability. The off state is an open circuit mode. The principal functions performed by the command circuitry include:

- Amplification of processed command pulse to operate relays
- Electrical isolation of spacecraft command lines from TEP circuitry. This isolation prevents any TEP internally generated voltage spikes from propagating into and either falsely triggering or damaging spacecraft command circuitry.
- Provide necessary timing, interlocking, and sequencing logic functions to ensure the command activates and/or deactivates proper circuits and that these circuits are in the proper electrical state.

Characteristics of each of the 20 command circuits are summarized in Table 4-1.

The command circuits are in two basic groups: those that utilize TTL logic and those that utilize discrete logic. In command circuits utilizing TTL logic, the command pulse is passed through an optically coupled isolator Q1-Q20 (Figure 4-5, sheet 3). This diode-to-transistor coupler (TI TIL103) electrically isolates the spacecraft command circuitry from any TEP electrical noise pulses. After transmission through the optically

Table 4-1. Command Circuit Characteristics

Command Title	Command and Logic Functions	Command Logic Type	Comment
Open TEP 76 volt (experiment) bus switch	Command pulse will close switch and electrically decouple TEP from experiments bus. Interlock prevents operation if TEP is drawing current from experiments bus.	Discrete	Lightweight switch related to only block 100 volts. Interlock prevents breaking
Close TEP 76 volt (experiment) bus switch	Command pulse will close switch and electrically connect TEP from experiments bus. Interlock prevents operation if TEP is drawing current from experiment bus.	Discrete	As above.
Special instrumentation on	Command pulse activates special instrumentation circuitry which separately powers and controls critical housekeeping temperature telemetry parameters (see 3.1.1.8)	Discrete	Permits monitoring of critical housekeeping functions when TEP is off
Substitute heater off	Command pulse deactivates substitute heater circuitry.	Discrete	

Table 4-1. Command Circuit Characteristics (Continued)

Command Title	Command and Logic Functions	Command Logic Type	Comment
Preregulator bypass	Command pulse activates bypass relay to close.	Discrete	Command sent in case of open failure in preregulator circuit.
Power supply enable	Command pulse activates instrumentation, instrumentation, internal supplies, and substitute heater circuitry while simultaneously deactivating cathode/collector supply.	Discrete	Deactivation of cathode/collector resets circuitry for sequenced turn-on
High voltage protection on	Command pulse activates overload circuit. This circuit allows PPS to be out of regulation due to overload or input line undervoltage for up to 0.4 seconds without damaging HV transformer secondaries due to excess dissipation.	Discrete	Circuit eliminates nusance shutdowns due to OST arcing. Current limit circuitry protects against arcing transients
PPS disable, substitute heater on	Command pulse deactivates instrumentation, internal and cathode/collector supplies while simultaneously activating the substitute heater circuitry.	Discrete	Substitute heater is activated when all other circuitry is off to maintain TEP above minimum storage temperature

Table 4-1. Command Circuit Characteristics (Continued)

Command Title	Command and Logic Functions	Command Logic Type	Comment
High voltage protection off	Command pulse deactivates high voltage protection circuitry, discussed above	Discrete	Failsafe mode in case protection circuitry malfunctions
All instrumentation off	Command pulse deactivates all instrumentation, including special instrumentation.	Discrete	Failsafe mode in case failure in instrumentation overloads spacecraft power bus
Cathode heater 100% power on	Command pulse activates cathode heater 100% setting, simultaneously deactivates heater power 110 and 120% settings. Interlock blocks command unless internal supply logic voltage $\leq$3.5 volts or if heater setting is not 50%.	TTL	Interlock threshold voltage level prevents scrambling of TTL logic. Requiring cathode heater to be 50% prior to turn-on assures preheat
Cathode heater 110% power on	Command pulse activates cathode heater 110% setting, simultaneously deactivating heater power 100 and 120% settings. Same interlocks as 100% setting discussed above.	TTL	

Table 4-1. Command Circuit Characteristics (Continued)

Command Title	Command and Logic Functions	Command Logic Type	Comment
Cathode heater 120% power on	Command pulse activates cathode heater 120% setting, simultaneously deactivating heater power 100 and 110% settings. Same interlocks as 100% setting.	TTL	
Cathode heater 50% power on	Command pulse activates cathode heater 50% setting and substitute heater, simultaneously deactivating cathode/collector along with 100, 110 and 120% heater settings. Interlock blocks command unless internal supply logic voltage $\leq$3.5 volts.	TTL	
Cathode heater power off	Command pulse deactivates all cathode heater power settings and cathode/collector while simultaneously activating substitute heater. Same interlock as cathode heater 50% power on setting.	TTL	
Anode and cathode/ collector on	Command pulse activates anode and cathode/ collector supplies while simultaneously de-activating substitute heater. Interlock blocks command if logic voltage $\leq$3.5 volts or if cathode heater at 50% setting.	TTL	Prevents TEP turn-on into cathode emission limited mode of operation

Table 4-1. Command Circuit Characteristics (Continued)

Command Title	Command and Logic Functions	Command Logic Type	Comment
Anode and cathode/ collector off	Reverse of anode and cathode/collector on command.	TTL	
Defeat excess body current protection	Command pulse blocks excess body current signals from shutting TEP off.	TTL	Allows failsafe operation with excessive body current or in event protection circuitry is malfunctioning.
Defeat excess pressure protection	Command pulse blocks excess pressure signal from shutting TEP off.	TTL	Allows failsafe operation with excessive pressure in OST or in event protection circuitry is malfunctioning.
Protection on and reset	Command pulse activates protection circuitry and resets fault telemetry signal to no output.	TTL	

coupled isolator, the resultant command pulse is routed through appropriate TTL logic for processing. Amplification of the signals to activate appropriate relays is provided by TTL driven LM008 National Semiconductor relay drivers (U7-U16 sheet 3 of Figure 4-5).

In those circuits containing discrete command logic, the command pulse is amplified by a 2N 2907 PNP transistor (Q21-Q30 on sheet 3 of Table 4-1), to drive appropriate relays after it is passed through an optically coupled isolator.

4.3.1.11 Protection Logic (Figure 4-5, Sheet 4)

Three protection circuits within the PPS automatically shut down the TEP if the sensed functions exceed predetermined limits. A brief description of each circuit is presented below:

1) Excess Body Current. An analog signal from the body current telemetry is sensed by a Harris HA2700 comparator (U1 on sheet 4). If the signal level corresponding to a 10 ± 1 mA body current is exceeded for 30 ± 20 msec, a pulse is generated by a 2N2920 transistor (Q1A on sheet 4). This pulse activates appropriate relays to turn off the cathode/collector supply and turn on the substitute heater circuitry. The pulse also triggers the fault telemetry to a 3 volt level which is indicative of excess body current.

2) Excess Pressure. An analog signal from the OST pressure telemetry is sensed by a HA2700 comparator (U2 on sheet 4). If the signal level corresponding to a 10 ± 5 μA ion pump current is exceeded for 30 ± 20 msec, a pulse is generated by the 2N2920 transistor (Q1B on sheet 4). This pulse activates appropriate relays to turn off the cathode/collector supply and turn on the substitute heater circuitry. The pulse also triggers the fault telemetry to a 1.5 volt level which is inidicative of an excessive ion pump pressure.

3) Undervoltage. A digital signal is generated within the cathode/collector supply (Figure 4-5, sheet 7) if an undervoltage condition occurs on the output of the 25 volt preregulator. This signal provides a 5 volt TTL high if the voltage is below a minimum acceptable level of 17 volts. The signal is used to trigger the fault telemetry to a 4.5 volt level. Protective circuitry that is used to provide the subject digital signal also shuts down the cathode/collector supply internally.

4.3.1.12 RF Telemetry (Figure 4-5, Sheet 4)

The RF telemetry circuitry receives two analog signals from RF diodes corresponding to output power and reflected power from the OST. Impedance matching and amplification of these signals to the desired 0 to 5 volt spacecraft telemetry system input levels are accomplished by HA2700 opamps (U7 and U8 on sheet 4).

4.3.1.13 Substitute Heater Control (Figure 4-5, Sheet 4)

When the TEP is off for extended periods of time, radiative heat loss from the south panel could cool critical components below safe temperature levels unless otherwise compensated for. Towards this end, appropriate levels of keep alive power are provided during inoperative periods by connecting the unregulated experiments bus across the terminals of a resistive substitute heater element. This heater element is bonded to the TEP baseplate. During periods when the TEP is operative, the substitute heater is disconnected from the experiments bus to prevent excessive power dissipation. The substitute heater control circuitry provides the switching functions upon stimulation from the command circuitry.

One side of the heater is permanently connected to the positive lead of the experiments bus. The other terminal of the heater element is connected to the negative lead of the experiments bus through two 2N5664 power switching transistors (Q5 and Q6, Figure 4-5, sheet 4). When an appropriate command signal is sent to their base drive, these transistors conduct and complete the ground of the circuit and allow current to flow in the heater element. The base drives of Q5 and Q6 are triggered by Q4, whose base-to-emitter voltage, in turn, is stimulated by a command pulse closure of relay terminals 2 and 6 (sheet 4).

This solid state switching approach was utilized to minimize weight, maximize reliability, and avoid the problems associated with space qualifying a switch capable of continuously making or breaking current at voltage levels up to 95 volts. Forward conduction losses in the solid state switches, although minimal, are no problem in this application where dissipation is the required operating mode.

4.3.1.14 Fault Telemetry (Figure 4-5, Sheet 4)

The fault telemetry circuit produces one of four different signal levels corresponding to a specified fault event:

Fault Indication	Signal Level (volts)
No fault	5.0
Excess body current	3.0
Excess pressure	1.5
Housekeeping bus undervoltage	0.0

The fault telemetry is triggered by a signal from the protection circuitry discussed previously in Section 4.3.1.11. After the first signal is received, the fault telemetry memorizes it and locks out all others. New fault signals register only after a protection enable command is sent to reset the fault telemetry to the 5 volt level.

4.3.1.15 High Voltage Telemetry (Figure 4-5, Sheet 10)

Resistive dividers are utilized to sense the critical high voltages of interest.

Sense Point	Divider Resistor Designation*	Circuit Board Number*
Cathode Voltage	R82/R92	A11
Collector 7	R79/R89	A12
Collector 5	R77/R87	A13
Collector 4	R76/R86	A13
Anode	R12/R13	A15(A)

*Figure 4-5, Sheet 12

A HA2700 opamp (U6-10, Figure 4-5, sheet 12) impedance matches the divider resistor output for each measurement to the spacecraft telemetry system. Direct impedance matching with the spacecraft is not possible without encurring excessive levels of power dissipation due to the combination of high sensing voltage levels and low input impedance requirements.

4.3.1.16 Collector Number 1 and Body Current Telemetry (Figure 4-5, Sheet 10)

The analog current level for each of the subject functions is sensed in a shunt resistor R70 for body current and R71 for collection 1 current. The resultant low voltage signals are then amplified in a HA2700 opamp to produce the design 0 to 5 volt range for the spacecraft telemetry system.

4.3.1.17 Pressure Telemetry (Figure 4-5, Sheet 10)

OST ion pump current, which is proportional to OST internal pressure, is measured across the 100 KΩ R3 shunt resistor (Figure 4-5, sheet 12). This signal is amplified and impedance matched in a HA2620 opamp (U5 Figure 4-5, sheet 10) with the resultant signal level being 0 to 5 mA. This signal is further amplified in the AR1 megamp (Figure 4-5, sheet 10) to the required spacecraft telemetry input level. A two stage approach is utilized to provide adequate isolation for this noise sensitive circuit.

4.3.1.18 Current Monitors

Low Voltage Current Monitors (Figure 4-5, Sheet 2). Classical ac excited megamp circuits are used to monitor the current in the experiments and housekeeping buses. A two core device, with two oppositely phased output windings, common control winding, and a common shorted control winding for stability, is used.

High Voltage Current Monitors (Figure 4-5, Sheet 11). The high voltage current monitors were developed to provide a mechanism for monitoring milliamp level circuits in each of the high voltage leads (Z1 through Z10 on sheet 11) without breaking the insulation to maintain high reliability. A single turn, balanced core megamp circuit concept was developed where active feedback is used to provide relatively low error (≤ 1 percent of full scale). In this approach, two preselected balanced cores are excited with a common ac signal. Unbalance occurring due to current flowing in the sensed lead is amplified in a HA2700 opamp (U1 on sheet 11) and the resultant output impressed across R6. A stabilization signal is achieved by feeding back the current through R6 to winding 5 in megamp AR1.

Offset nulls within acceptable limits are achieved by specially selecting and balancing all components in the ac loop. The selected components include megamp AR1 cores, rectifying diodes CR1 and CR2, and load resistors R2 and R3.

4.3.1.19 Fault Clearing Relay (Figure 4-5, Sheet 1)

The fault clearing relay provides a mechanism for electrically decoupling the TEP from other loads on the experiments bus. This operation is performed only if an internal fault causes the TEP to short out the experiments bus. Under such a condition the experiments bus is decoupled from the solar array by the spacecraft switchgear. After no current is flowing through the TEP a command pulse is sent to open the fault clearing switch. As discussed in Section 4.3.1.10, command logic interlocks prevent the fault clearing switch from being activated open if a command is sent while current is flowing. Once the TEP fault clearing relay is opened, the solar array is reconnected to the experiments bus permitting operation of other loads. During normal operation, the TEP fault clearing switch is in a closed contact configuration.

The selected PT4-2350 relay is designed to block up to 100 volts, but not to break the experiments bus current. This relay was selected, in lieu of a more complex high voltage switch capable of breaking up to 10 amps of TEP current, to minimize volume and weight.

4.3.2 Nonstandard Components

In producing the PPS, it was necessary to develop and/or space qualify a number of high voltage components to meet the relatively stringent operating requirements. Of principal concern was the ability of these components to provide stable operation over a 2-year life when subjected to relatively high dc and ac voltages, and thermal stress levels in space. A description of these components, along with a summary of qualification errors, is presented in the following paragraphs.

4.3.2.1 High Voltage Transformer

The high voltage transformer (T3 in Figure 4-4) steps up the regulated 55 volt output of the chopper inverter circuit to the required cathode and multiple collector voltage levels. A schematic diagram of this device is presented in Figure 4-6. Each of the ten identical series-connected secondaries produces a nominal output voltage of -1.13 kV. When all collector outputs are summed together to form the cathode output, the nominal voltage level is -11.3 kV, corresponding to a total stepup ratio of 208:1.

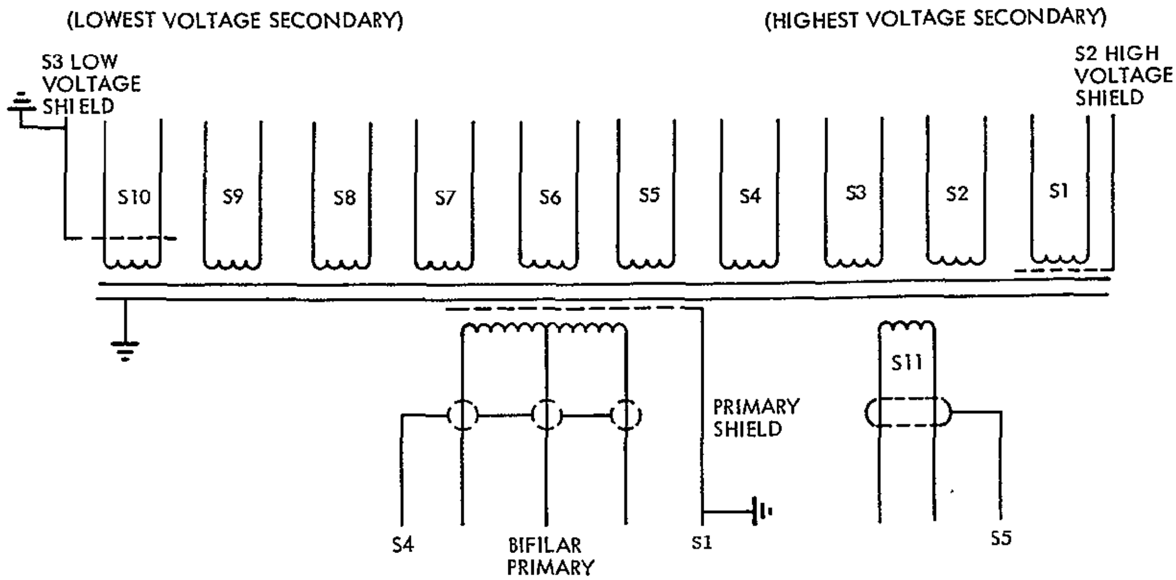


Figure 4-6. High Voltage Transformer Electrical Schematic

The design requirements for the high voltage transformer are summarized in Table 4-2. The transformer design was rated to meet the higher corona test voltage levels specified in column 2 for continuous operation in vacuum under the specified thermal conditions. The transformer was also designed to operate corona-free after being exposed to the induced voltage and dielectric, withstanding stress levels listed in columns 3 and 4. Design verification tests performed on an early development model established performance capabilities greater than the requirements listed in Table 4-2.

A configuration sketch of the high voltage transformer is shown in Figure 4-7 along with a picture of the device as installed on the PPS baseplate. Key design features are summarized below:

a) Each layer is separately rectified to provide nine of the ten outputs. The first two layers are combined to form the first stage output.

b) A single layer winding for each of the outputs produces low winding to winding ac voltage stress.

c) Improved coupling, required to minimize output ripple and reduce output dissipation through the reduction of secondary rms currents, is achieved by inverting the secondary windings. The highest voltage secondary, which circulates the highest current, is placed closest to the primary to provide optimal coupling. The lowest voltage secondary is located furthest from the primary, but since it contains the minimum output current level, coupling is not as important.

Table 4-2. High Voltage Transformer Design Requirements

	Maximum Space Operating Voltage Levels(4)		Flight Screening Tests					
			Corona(1)		Induced Voltage(2)		Dielectric With-standing(2)	
	Column 1		Column 2		Column 3		Column 4	
	KVDC	KVAC (3)	KVDC	KVAC	KVDC	KVAC	KVDC	KVAC
Low voltage secondary to low voltage shield (S3 to S10)	0.58	±0.58	1.5	±1.55	1.16	±1.16	1.42	±1.42
High voltage secondary to high voltage secondary (S9 to S10 typical)	1.16	0.06	1.5	±0.28	2.32	±0.12	2.81	±0.15
High voltage secondaries to core								
S10 to core	0.58	±0.58	0.75	1.55	1.16	±1.16	1.48	±1.48
S9 to core	1.74	±0.58	2.26	1.55	3.48	±1.16	4.44	±1.48
S8 to core	2.90	±0.58	3.77	1.55	5.80	±1.16	7.40	±1.48
S7 to core	4.06	±0.58	5.28	1.55	8.12	±1.16	10.36	±1.48
S6 to core	5.22	±0.58	6.79	1.55	10.44	±1.16	13.31	±1.48
S5 to core	6.38	±0.58	8.29	1.55	12.76	±1.16	16.27	±1.48
S4 to core	7.54	±0.58	9.80	1.55	15.08	±1.16	19.23	±1.48
S3 to core	8.70	±0.58	11.3	1.55	17.40	±1.16	22.19	±1.48
S2 to core	9.86	±0.58	12.8	1.55	19.72	±1.16	25.15	±1.48
S1 to core	11.02	±0.58	14.3	1.55	22.04	±1.16	28.11	±1.48

(1) Corona level <5 pc for impressed voltage levels.

(2) Apply specified voltages for 5 seconds. No evidence of arcing, breakdown, or damage shall be observed.

(3) Peak voltage impressed on AC.

(4) 2 years continuous operation at a baseplate temperature of 40°C and a hotspot (winding S1) temperature of 86 to 92°C. Also 170 thermal cycles where baseplate temperature varies between -10 and +40°C with voltage applied.

d) A shield S1 (Figure 4-6) returned to ground surrounds the primary windings to prevent capacitive coupling between secondary and primary winding. If present, transients induced into primary windings by such coupling could lead to overstress of critical semiconductor elements.

e) A shield S2 inside the secondary windings is intentionally left open. This shield, in early designs, was initially returned to the high voltage dc output to reduce capactive coupling between the innermost secondary winding and the shield S1 to minimize output ripple. Subsequent circuit development obviated the need for shield and it was therefore left floating.

f) A shield S3 surrounding all the high voltage secondaries is returned to ground. This shield was found necessary to reduce the ripple between windings 4 to 5 in addition to the feedback winding loads.

g) A shield S4 surrounding the primary windings, and a shield S5 surrounding the feedback windings, are required to prevent high voltage arcs from coupling into the windings.

h) A 1 mil supermalloy core was used to provide low loss (<5 watt/pound) at the 10 kHz and 5 k gauss operating conditions. A C core geometry was selected to permit the selected layer winding approach. Gaps of ≤ 1 mil were used to closely approach the open circuit inductance of an ungapped core and thus reduce exciting current losses.

i) The maximum level of ac voltage stress on the dielectric system was controlled to ≤ 10 volts/mil while the maximum dc stress was controlled to ≤ 60 volts/mil. Such stress levels are well below the 150 volts/mil stress rating of the insulation system selected. Such a safety factor ensures a long life.

j) A sandwich polyester barrier material was placed between all high voltage windings (prior to impregnation) to ensure cracks could not propagate during space operation. Polyurethane (PRC1570) was selected as the impregnating agent. Its high tear strength and flexibility provide the desired corona resistance when the transformer is subjected to thermal cycling in vacuum.

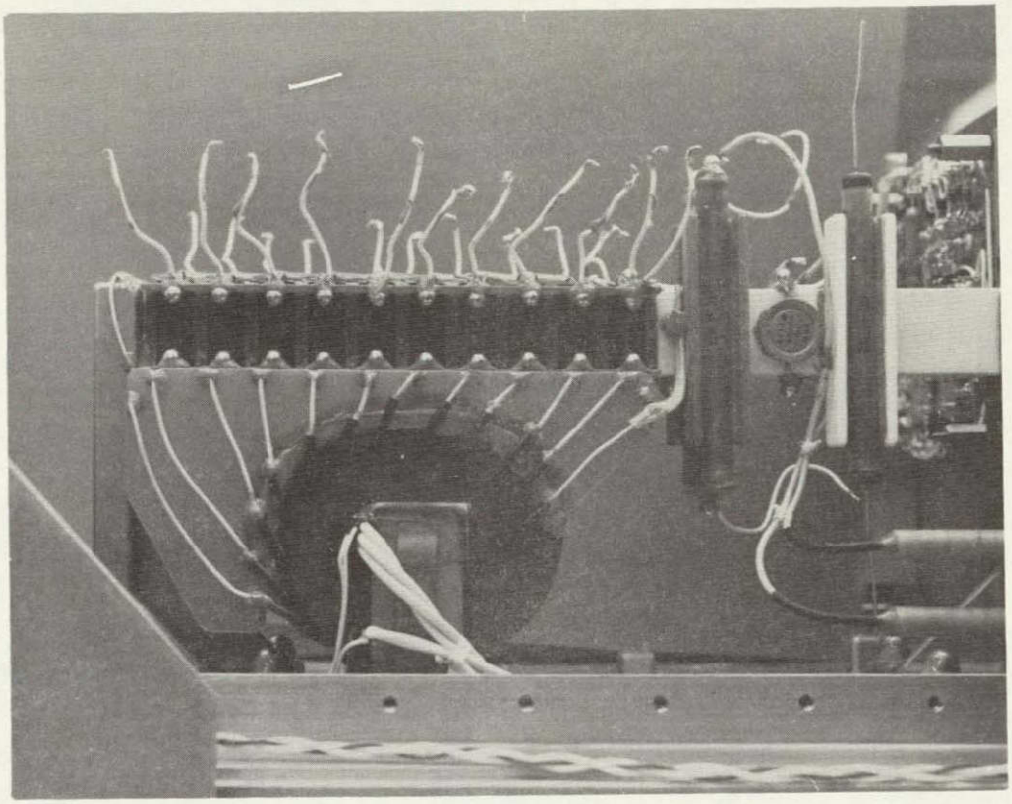


Figure 4-7. High Voltage Transformer Mounted to PPS Baseplate During Early Assembly Stages

A summary of the high voltage transformer acceptance and qualification test program is presented in Table 4-3. Heavy emphasis was placed on corona testing to nondestructively identify any microfissure in the insulation system. Four corona tests were used during the qualification cycle, with an additional two screening tests during manufacturing. The pass criteria required that the peak charge level for a corona bust ≤ 5 picocoulombs (pc), with the maximum acceptable corona burst rate being ≤ 1 per minute. The selected criteria for peak charge level is based upon cable industry practice, where a 50-year underground high voltage polyethylene cable is tested to a 5 pc standard with no limit on burst rate. The 5 pc limit was extrapolated to be much more conservative for the TEP application since the polyurethane/estermat insulation system is significantly less corona sensitive than the polyurethane insulation system. The corona burst rate level ≤ 1 per minute represented the lowest detection rate compatible with the noise sensitivity of the corona test instrument used. The aforementioned corona test acceptance levels were found to work satisfactorily for the TEP application. It is clear, however, that a significant

Table 4-3. Transformer

Test Title and Order	Measurables and/or Approach	Qual	Acceptance Screening
Electrical performance	Insert T3 in test PPS circuit, verify all circuit performance parameters are acceptable	x	x
Corona	Per column 2 of Figure 11	x	x
Induced voltage	Per column 3 of Figure 11	x	x
Dielectric withstanding voltage	Per column 4 of Figure 11	x	x
Thermal cycling	Nonoperating, 10 cycles −30 to +90°C 90 minutes at temperature, 30 minute transition	x	x
Vacuum bakeout	Expose transformer to 90°C vacuum oven ($<10^{-5}$ torr) for 48 hours to stress relieve insulation	x	x
Dielectric withstanding	Per column 4 of Figure 11	x	x
Insulation resistance	Measure insulation resistance between all transformer terminals. Pass values $\geq$10 MΩ	x	x
Electrical characteristics	Resistance, inductance, leakage inductance, turns ratio, interwinding capacitance, etc.	x	x
Corona	Per column 2 of Figure 11	x	x
Thermal shock	Nonoperating, 10 cycles −30 to +90°C in 2 minutes. Verify electrical discontinuity does not occur between any terminals during thermal exposure	x	
Vibration	Test in all three perpendicular axes at sweep rate of half octave/minute sinusoidal spectrum in note (1)	x	
Corona	Per column 2 of Figure 11	x	
Accelerated life in thermal vacuum	Operate in thermal vacuum for 1170 hours at transformer hot spot temperatures ≈20°C hotter than maximum predicted space operating tempera.	x	
Thermal CY	While operating at full current and voltage perform 17 thermal cycles between −20 and 100°C hot spot temperature		
Corona	Per column 1 of Figure 11		

(1) 20 to 100 Hz constant 0.2 inch double amplitude, 100 to 200 Hz constant acceleration 100g peak, 200 to 2000 Hz constant acceleration in 10g peak.

amount of research activity is needed before a more rigourous correlation between lifetime and corona test acceptance levels can be established.

Another critical test in the high voltage transformer space qualification was the accelerated life test. In this test, the transformer was operated in thermal vacuum at the maximum operating voltage levels (e.g., cathode voltage 11.6 kV). The transformer hot spot (S1 winding) temperature was forced to considerably higher temperature levels than that predicted for space operation* to provide an accelerated test condition. The temperature time history for this test was:

Hot Spot (S1 Winding) Temperature (°C)	Operating Time in Thermal Vacuum
105	620
110	490
115	60

An insitu hot spot temperature measurement was performed by measuring the winding resistance at operating temperature and comparing it to a control measurement taken previously at room temperature.

Comparison of corona and electrical performance measurements at the midpoint and end of the lifetest with those control measurements performed prior to the start of the lifetest indicated no degradation of electrical performance or high voltage integrity.

No problems were encountered in any other of the qualification tests, and all flight transformers were found to operate satisfactorily.

4.3.2.2 Pulse Limiting Resistors

Arcs occurring on the output terminals of TEP high voltage filter capacitors can produce uncontrolled oscillations with peak current levels on the order of thousands of amps, unless otherwise compensated for. OST and PPS reliability considerations dictate that such capacitive discharges be critically damped and limited to $\leq$100 amps. Towards this end, specialized multilayer metal oxide film pulse limiting resistor were developed and space qualified for the TEP program. These resistors, which must

*The worst-case hot spot temperature range was predicted to be 86 to 95°C over 2-year mission life.

Table 4-4: TEP Pulse Limiting Resistor Procurement Ratings

Nominal DC Resistance (ohms)	Max Rated Steady State Power (watts)	Max Rated Peak Pulse Power (watts)	Max Rated Continuous Working Voltage (volts)	Max Rated Pulse Voltage, V_r (volts)	Rated Pulse Energy Absorption Capacity (joules)	Test Capacitance C_T (μF)
50	3	80,000	12	2,000	0.3	0.150
50	4	320,000	14	4,000	0.12	0.015
15K	10	9,600	387	12,000	0.72	0.010
170	7.5	1,510,000	35	16,000	1.28	0.010
1K	5	400,000	70	20,000	2.00	0.010
300K	2	136	772	6,400	10.50	0.510
500	10	290,000	70.7	12,000	0.72	0.010
1000	10	144,000	100	12,000	0.72	0.010

dissipate peak power stresses up to six orders of magnitude greater than steady state stresses, are placed in the output leg of each high voltage filter capacitor. The resistance level is optimized to minimize steady state power dissipation while still limiting peak current $\leq$100 amps during an output fault.

The requirement that the resistor be rated to simultaneously withstand high voltage, and peak power eliminates most candidate devices from consideration with the exception of the selected multilayer metal oxide film resistors. Wire wound resistors, although capable of withstanding the high peak power levels, are susceptible to high voltage breakdown. Carbon film resistors were found to fail open at the high peak power levels of interest. Carborundum globars, commonly used in terrestrial applications, do not adequately support high voltage stress levels and are much too large and heavy.

Procurement ratings for the TEP pulse limiting resistors are presented in Table 4-4. All values incorporate safety margins over nominal operating conditions to ensure high reliability operation over the 2-year mission life. Rated pulse energy absorption capacity* was sized to provide a 400 percent safety margin over nominal operating levels. This safety margin was demonstrated during space qualification testing of the devices. The test circuit illustrated in Figure 4-8 was utilized to perform these tests. Test filter capacitor C was charged to rated voltage levels and the resultant energy discharged through the pulse limiting resistor by the cam operated switch. The resistors were subjected to 1000 such pulses without degradation. A similar procedure was utilized for screening flight devices, except the charging voltage level was lowered to nominal operating conditions and the device was subjected to 200 pulses. Acceptance criteria for performing these flight screening and qualification tests were established during a development program where a variety of candidate devices was subjected to 10,000 pulses at energy absorption levels ranging between 100 and 1000 percent of nominal operating levels.

---

*Rated energy absorption capacity $\equiv \frac{1}{2} \left(\text{Test filter capacitance}\right) \left(\text{rated voltage}\right)^2$

Operating energy absorption capacity $\equiv \frac{1}{2} \left(\text{TEP filter capacitance}\right) \left(\text{nominal operating voltage}\right)^2$

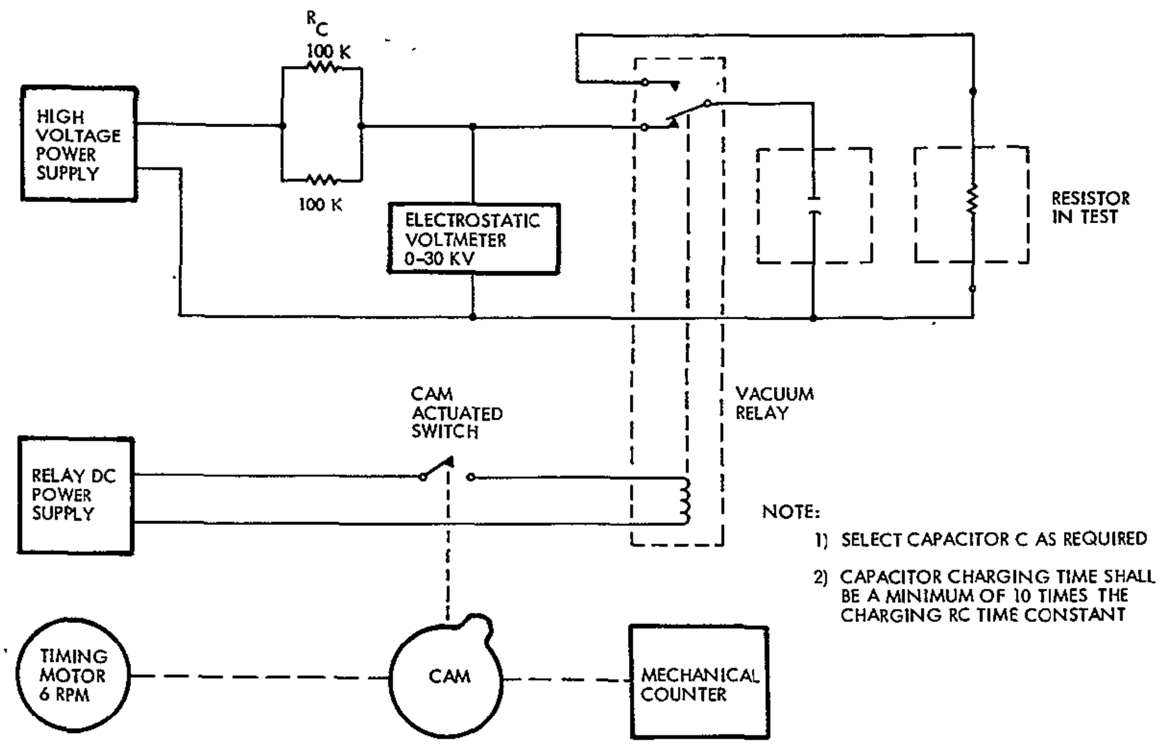


Figure 4-8. Resistor Pulse Voltage Test Circuit

4.3.2.3 Anticorona Sphere

The anticorona sphere was developed for the TEP program to ensure adequate repeatability and quality control of the over 100 high voltage terminations required per unit. In prior applications high voltage terminations were individually formed by skilled operators using a solder ball technique. Such an approach was found unacceptable for TEP application because of the cost and surface control problems associated with the large number of terminations to be made.

A cross-sectional view of the anticorona termination sphere is presented in Figure 4-9. Wires to be terminated or connected are fed into the cylindrical cavity drilled in one side of the sphere. Solder is fed into the cavity from the open hole at the bottom. Surface tension pulls the solder up into the cavity and pushes entrapped air out through the solder blow hole at the top. Solder is fed into the base until the blow hole is completely filled. Epoxy is used to bond the ball to a nonmetallic support to provide adequate rigidity to survive launch.

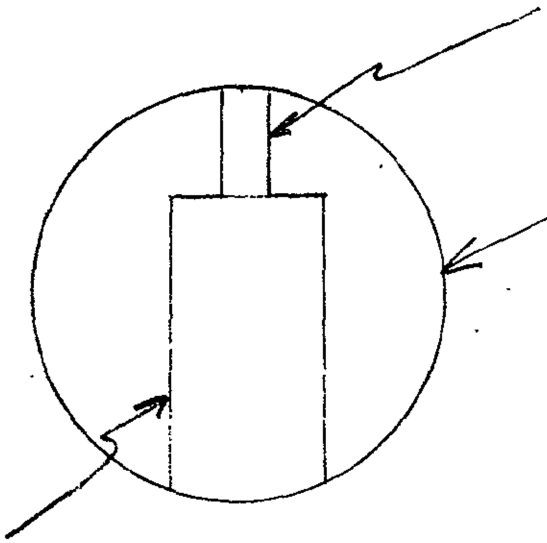


Figure 4-9. Cross-sectional View of Anticorona Sphere

The ball size was selected to ensure corona free operation in air and vacuum at voltage levels as high as 14 kV, air/vacuum gap field strengths $\leq$20 volts/mil, and surface creepage fields of $\leq$8 volts/mil.

A picture illustrating the anticorona spheres that are used to terminate connections between the high voltage transformer secondaries and the output bridge rectifiers was presented in Figure 4-7. Ten pairs of anticorona spheres can be observed in the upper portion of this picture.

Over 500 anticorona spheres were installed in TEP units during the course of the TEP program. Quality assurance rejections or acceptance testing failures were not observed. Installation time was found to be less than a few minutes per termination. The anticorona sphere termination was space qualified during system level environmental and electrical test on the QF01 PPS unit.

4.4 PACKAGING DESIGN

4.4.1 General Considerations

A hybrid open construction technique was selected for packaging the TEP. This was the only one of five candidate approaches found to be compatible with the TEP weight, power dissipation, maximum envelope, ground test, maximum operating voltage, and lifetime requirements. In this approach all components, with the exception of the high voltage transformers, are bonded directly to circuit boards, heat sinks, or other supporting structure without enclosing them in insulating materials such as pressurant gases, dielectric fluids, potting materials, foams, or gels. The inherent insulating properties of space vacuum or ambient air were found completely acceptable for providing corona free high voltage standoff.

The components and output high voltage circuitry were designed to withstand any occasional high voltage arcs that might occur due to local changes in operating environment. However, it was necessary to encapsulate the high voltage transformer, since if left open an arc occurring between secondary and primary windings could propagate into the low voltage primary circuitry and potentially cause a serious component failure. Furthermore, it was found necessary to encapsulate the secondary windings of the high voltage transformer to allow adequate thermal conductivity to the baseplate. Finally, it was deemed desirable to encapsulate the high voltage transformer to eliminate potential contamination problems during handling and to provide a rigid structure. The relatively small size of these transformers allowed encapsulation without any significant weight penalties.

A summary of the general ground rules utilized in the packaging of the PSS is presented in Table 4-5. A description of the configuration of this device is presented in the next sections.

4.4.2 PPS Configuration

4.4.2.1 External Configuration

The PPS (Figures 4-9 and 4-10) contains 1120 electronic parts. These parts are packaged in a sheet metal enclosure 52.1 cm (20.5 inches) long, 24.1 cm (9.5 inches) wide, and 17.8 cm (7 inches) high. The sheet metal enclosure bolts to a 0.63 cm (0.25 inch) thick baseplate. The entire PPS assembly weighs 13.3 kg (29.28 lbs). The PPS baseplate extends beyond the enclosure walls on three sides to give a total area of 968 cm^2 (150 in^2). One of these edges, on the right side of Figure 4-9, provides a mounting surface for two substitute heaters each 22.9 cm (9 inches) long by 2.5 cm (1 inch) wide. The other two edges, in the foreground and left side of Figure 4-9, provide the area required for mounting the OST, heat pipe evaporator saddle, and some of the fasteners necessary for mounting the TEP to the spacecraft south panel platform. The PPS baseplate has a total of 43 fasteners, 18 to 32 nutplates and thread inserts, for spacecraft mounting.

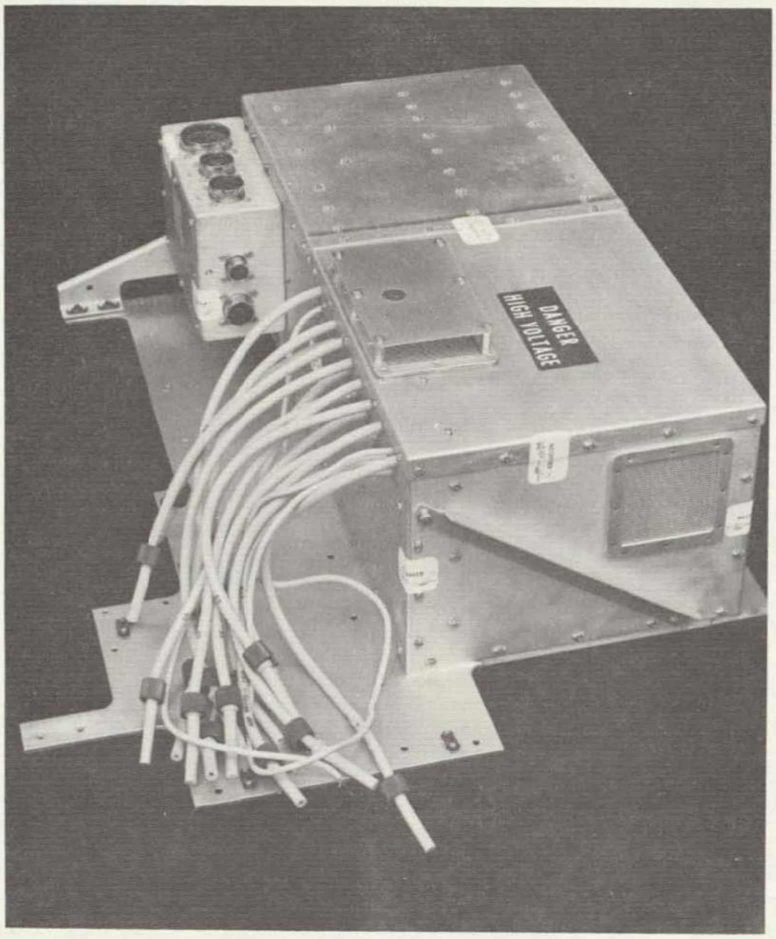


Figure 4-9. PPS Prior to Integration with OST

A picture of the PPS integrated with the OST and a heat pipe evaporator saddle simulator is presented in Figure 4-11. The heat pipe saddle is placed between the OST and the PPS baseplate. These components are connected together by placing screws into through holes in the bottom of the PPS baseplate and heat pipe saddle and securing them in nut plates in the base of the OST. Desired stiffness, $f_r \geq 150$ Hz, is obtained by bolting the OST to the forward face of the PPS. This is done with brackets at the fore and aft end of the OST structure (Figure 4-11). The multiple depressed

Table 4-5. TEP Packaging Ground Rules

Electric Fields	
Solid dielectric	50 volts/mil
Air or vacuum gap	20 volts/mil
Surface creepage	8 volts/mil
Voltage Derating	
Rated voltage = (1.33) x (operating voltage)	
Vacuum Environment	
Venting	$\geq$2 cm^2/1000 cc of enclosed volume
Maximum operating pressure	$\geq$1 x 10^{-5} Torr
Nonmetallic materials	Vacuum bake to drive off volatiles prior to assembly
PPS unit	Vacuum bake in isothermal oven at 150°F for 48 hours prior to initial operation in vacuum
Circuit Isolation	
All circuitry $\geq$250 volts mounted in grounded high voltage enclosure	
All circuitry $\leq$250 volts mounted in separate grounded low voltage enclosure	
Electrical isolation of high voltage and low voltage circuitry	
Operating Hot Spot Temperature	
Dielectrics under high voltage stress	$\leq$85°C
Low voltage electronic components	TRW Electronic Components Handbook standard derating
High Voltage Circuit Boards	
Corona free, by test, prior to installation to rated voltage level	
Ability to withstand breakdown internal to PPS high voltage enclosure without any damage	
Mechanical Loads	
Maximum circuit board deflection $\leq$0.0889 cm (0.035 in) under qualification level launch loads specified in Section 5.1	

Table 4-5. TEP Packaging Ground Rules (Continued)

High Voltage Components*	
Rated voltage	≥(2) x (operating voltage)
Rated current	≥(2) x (operating voltage)
Corona free at rated voltage level	
Materials	
Structural	5051 T4, aluminum (chem film processed)
High voltage circuit boards tested with ultrasonic probe (Reference 2)	Dense polyimid
Heat sinks	Beryllium oxide
Compliant cement	Epoxy (Lefkoweld)
Thermally conductive cement	Epoxy (tricast)
Impregnate	Urethane (PRC 1570)
High voltage encapsulant	Vacuum distilled silicone

*Except high voltage transformer described in Section 4.3.2.1

collector, white cylinder in right hand portion of the photo, is cantilevered off the aft end of the CTS south panel. Launch loads for this cantilevered mass, approximately 4.5 kg (10 pounds), are reacted to the spacecraft hardpoints through the OST and PPS structure. The TEP structure is extended to the spacecraft hardpoints with the two truss structures in the foreground of Figure 4-11 and the two rear corners of the PPS enclosure.

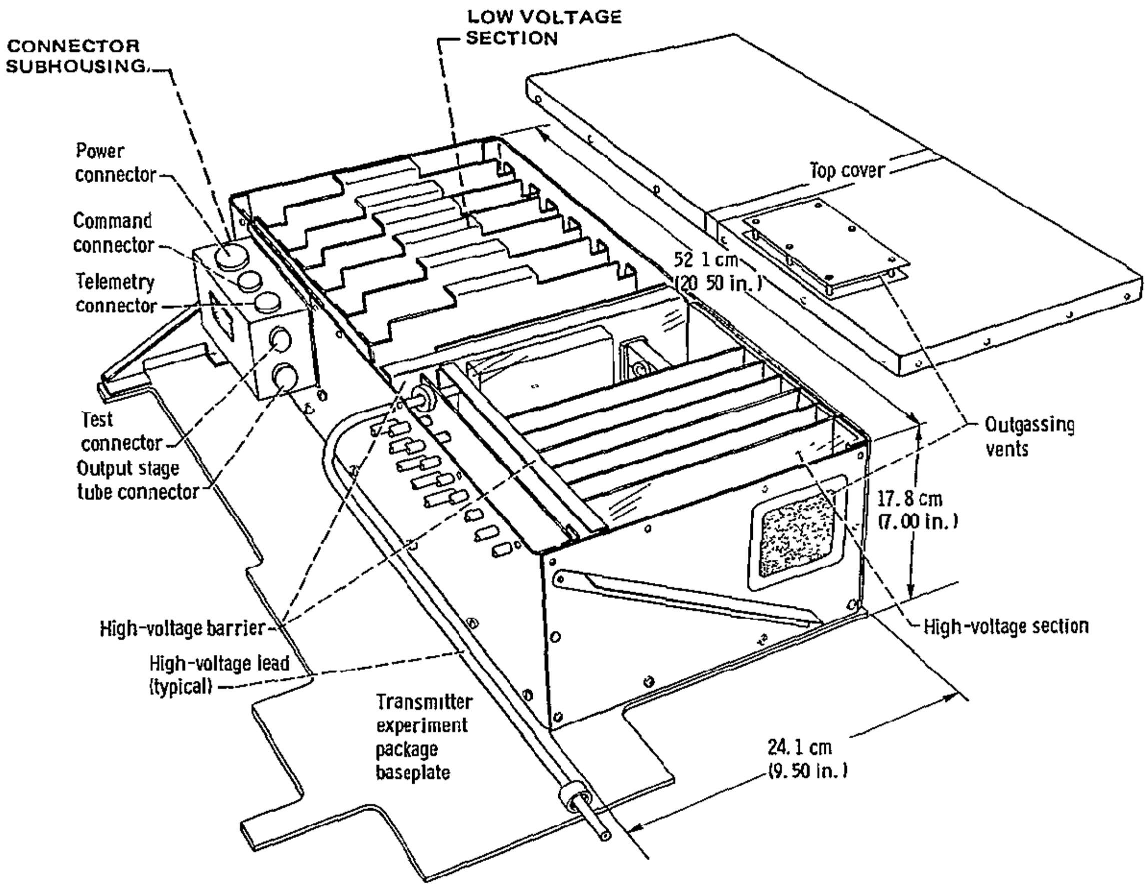


Figure 4-10. PPS Exploded Schematic

Five input-output connectors are topside mounted on a subhousing 15.2 cm (6 inches) by 6.6 cm (2.6 inches) wide and 10.9 cm (4.3 inches) high. Seventeen high voltage cables egress from the same enclosure wall as the subhousing, as seen in the upper left portion of the photo. These cables connect to the cathode, ion pump, and ground on the OST.

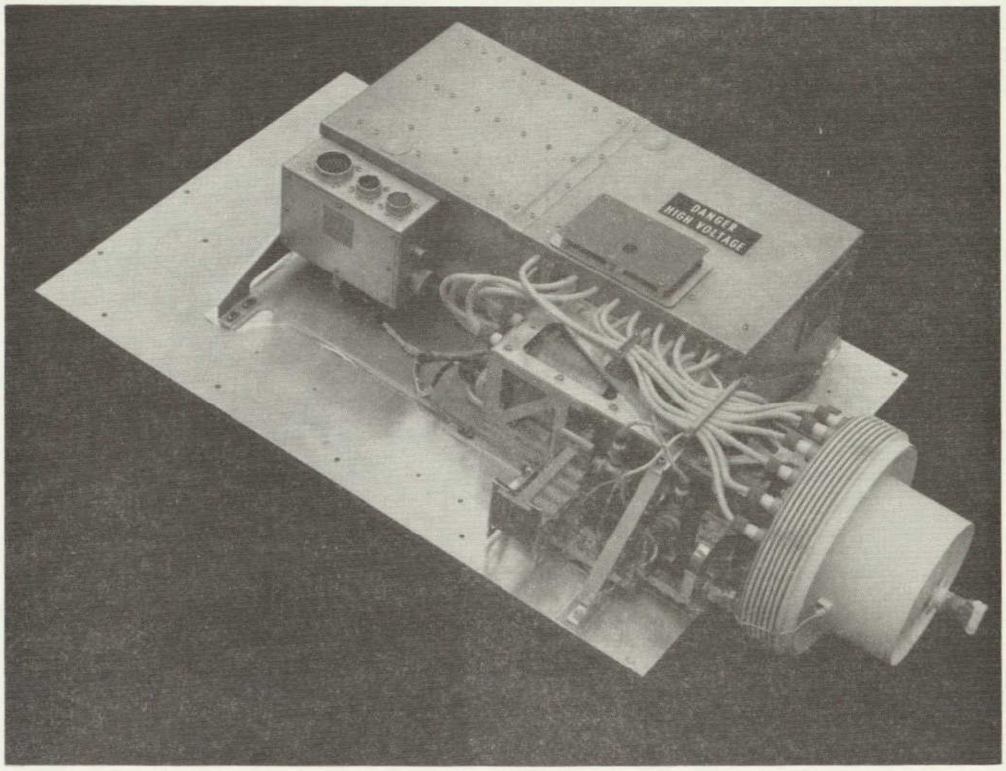


Figure 4-11. PPS Integrated with OST and Heat Pipe Saddle Simulator

Three side walls have EMI screened openings totaling 75.5 cm^2 (11.7 $inches^2$) of effect vent open area. The top vent has a flat epoxy glass cover placed 1.27 in (0.5 inch) above it. This cover prevents the spacecraft thermal blanket from blocking effluent gases.

Three removable covers provide ready access to the PPS circuit boards. These elements (Figure 4-10) include high voltage module, low voltage module, and connector subhousing cover. Further access to any of the circuit boards is accomplished by removing any one of the six side wall panels.

4.4.2.2 Internal Configuration

All electrical components, with the exception of the two resistive substitute heater elements discussed previously, are mounted in three physically isolated sections: connector subhousing, low voltage module, and high voltage module. The connector subhousing is separated from the low voltage module by a PPS wall panel. The low voltage module is separated from the high voltage module by two metallic grounded bulkheads.

The connector subhousing contains the electrical circuitry illustrated in Figure 4-5, Sheet 1, and includes the fault clearing relays, temperature sensors, and power line RF filters. A picture of the inside of this assembly is presented in Figure 4-12.

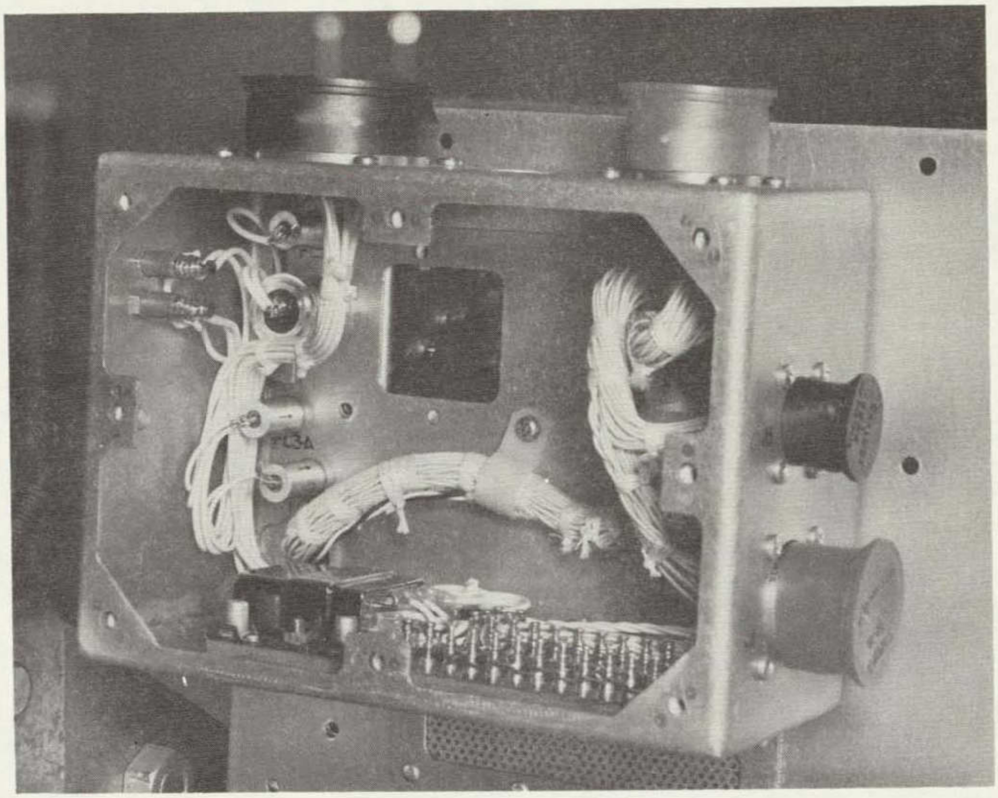


Figure 4-12. Connector Subhousing

The low voltage section (Figure 4-10) contains nine circuit boards. The boards in the low voltage section include circuits in Figure 4-5, sheets 1 through 11. Five of these circuit boards have connectors and are easily removable from the PPS. Four of the boards do not have connectors and are hardwired to the baseplate wire bundle to minimize lead impedance of critical circuits. Circuit breaks for connections are made at points which minimize harnessing, provide even circuit board component distribution, and do not compromise electrical function. All electrical power dissipation on the circuit boards is conducted to the PPS baseplate. The baseplate is cooled by conduction through the south panel to which it is attached. Heat from the south panel is rejected directly to space by radiation. The vertically mounted circuit boards, when bolted to the PPS cover sheets and baseplate, form a structurally efficient enclosure.

The cathode heater transformer, seen in the lower center portion of Figure 4-13, is mounted to the baseplate by a bracket. Although the internal portion of this device is at high voltage, it is impregnated with hysol epoxy insulation and coated with a conductive epoxy ground shield to preserve the electrical integrity of the low voltage module. The two high voltage secondary leads are rigidly encapsulated in estermat/hysol tubular structures, which pass through mating holes in the grounded bulkhead between the high and low voltage modules. These output leads attach to the high voltage cathode heater secondary output rectifier filter.

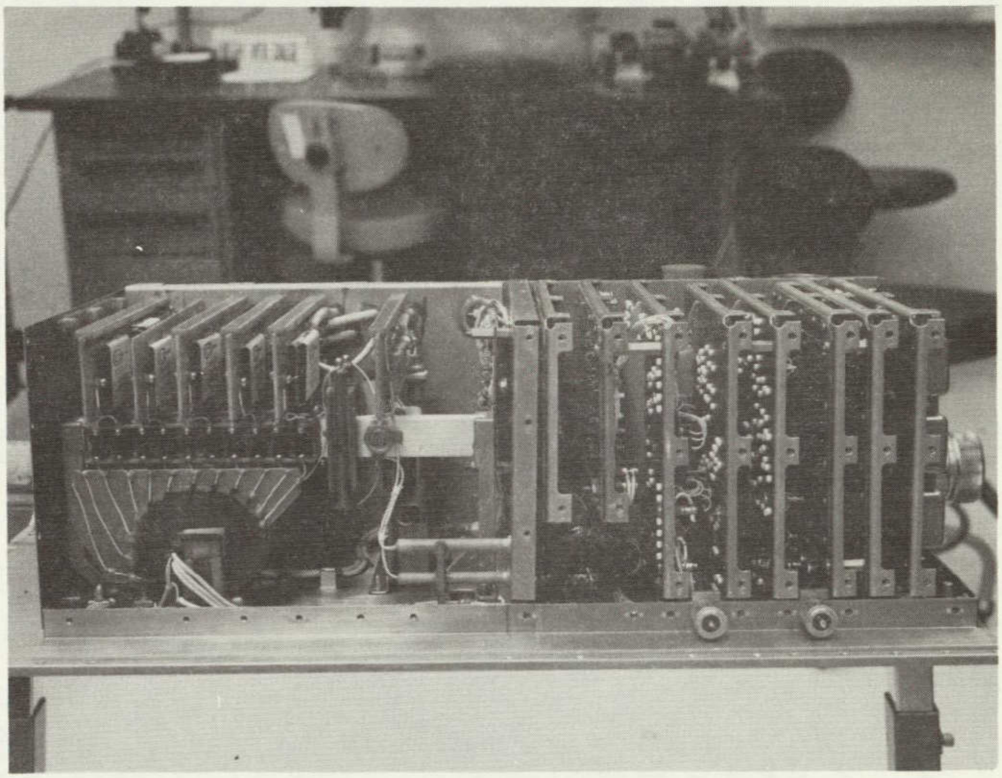


Figure 4-13. Internal View of PPS Looking From Rear Side (Substitute Heater Strip)

The high voltage current monitor board, illustrated schematically in Figure 4-10, has a high voltage PPS output lead passing through each pair of cores. This circuit board is electrically isolated from the high voltage module by a grounded bulkhead. All circuitry associated with the current monitors is mounted on the same metal terminal board as are the cores. A picture of this board is presented in Figure 4-14. Five of the 10 high voltage collector current monitor core pairs can be seen on this picture. The remaining five cores are on the reverse side of the board.

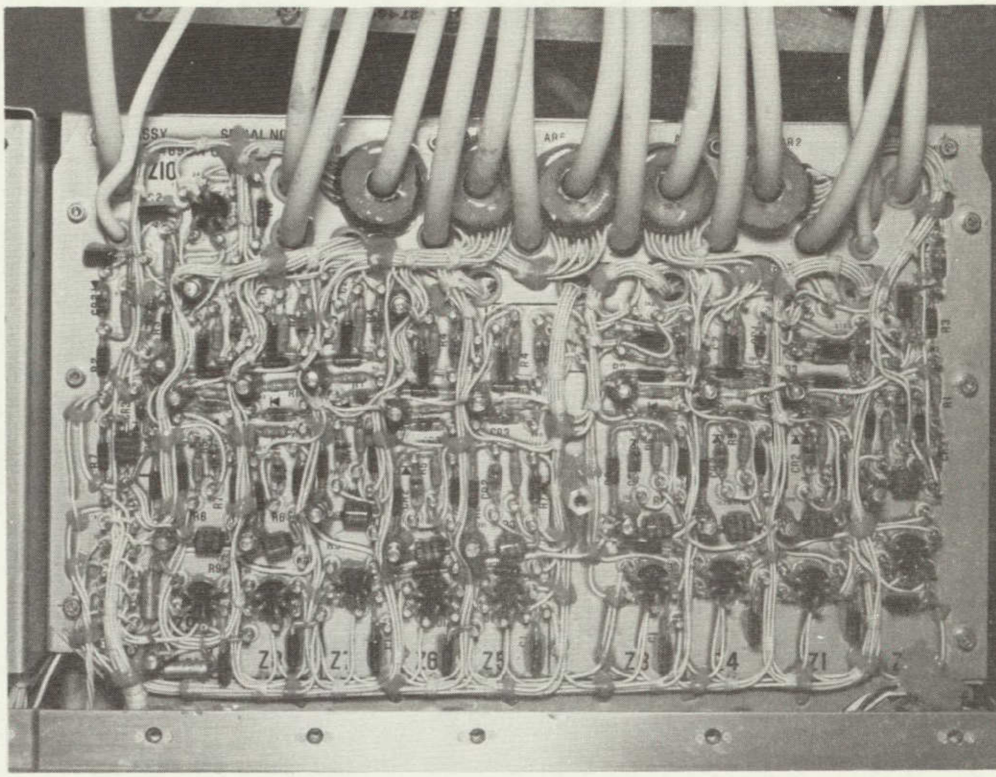


Figure 4-14. High Voltage Current Monitor Board

The high voltage section is housed in a separate grounded enclosure to prevent any internal arcs from propagating into and damaging sensitive low voltage components. All high voltage components and support structures have been designed to withstand internal arcing within the high voltage section without any degradation. Electrical buffer components protect devices in the low voltage section from any transients that might propagate on ground lines.

The high voltage section contains six circuit boards, the high voltage step-up transformer, and a beryllium oxide heat sink. The high voltage transformer is first mounted to the baseplate at the rear of the PPS container along the edge nearest the substitute heaters. The beryllium oxide heat sink, containing the high power dissipating bridge network and resistor assembly components, is then mounted directly above the transformer supported from both ends by vertical aluminum supports (see left hand portion of Figure 4-7). Metal and epoxy-cased diodes are attached directly to the beryllium oxide bar with an epoxy bonding agent (Lefkoweld). Brittle components, such as the ceramic core resistors, are partially encased in an intermediate layer of polyolefin shrink tubing. It was necessary to limit the maximum length of the polyolefin sleeving to $\leq$1.5 cm to prevent entrapment of gases that could cause high voltage breakdown. The polyolefin casing is bonded to the beryllium oxide heat sink. In this manner, it is possible to firmly bond the resistors to the heat sink and still allow for differential thermal expansion and prevent thermally induced stress cracks. No compromise in structural, thermal, or high voltage integrity was found in this approach.

Six high voltage circuit boards are mounted vertically, transverse to the beryllium oxide bridge network assembly, and are L-shaped to allow them to span over the network assembly (Figure 4-13). These boards are fastened to the PPS enclosure on three sides: to the baseplate, the full height of the wall adjacent to the OST, and to the upper portion of the opposite wall. The high voltage wiring between the transformer, bridge network, and high voltage circuit boards is assembled point to point, using the anticorona spheres discussed previously to form all terminations. Enough service loop is provided in each line to allow for dynamic deflections between assemblies during launch.

Seventeen high voltage output cables are individually routed from the component boards, through grommets in the high voltage barrier, through the high voltage current monitor board, and out through the PPS enclosure wall (Figure 4-10). These cables have properly dressed lengths to mate with OST connectors. Cable clamps are attached to the OST structure to constrain cable movement during launch (Figure 4-11, right foreground).

The high voltage circuit board to the extreme left of Figure 4-13 contains the ion pump anode supplies. The five boards to the right of the ion pump/anode board contain the output circuitry, less bridge network, for each of the 10 collectors and cathode heater. Circuit board voltage levels are graded. The lowest voltage circuit board anode supply is closest to the grounded enclosure on the left of Figure 4-13, and the highest voltage cathode circuitry is in the center of the high voltage section.

All of the high voltage circuit boards are made of 0.24 cm (0.093 inch) thick polyimid laminate material. A comprehensive materials investigation program performed during the development phase indicated that dense polyimid was much superior to glass epoxy board for the high voltage and high temperature TEP operating conditions. This investigation also indicated that nondestructive ultrasonic probing of the polyimid boards was necessary to screen out material containing nonvisible internal voids. Such voids were found to be corona sensitive and compromised high voltage integrity.

A picture of a typical high voltage circuit board at a partial assembly stage is presented in Figure 4-15. This board, as all others, has a partial 0.16 cm (0.063 inch) aluminum frame with attachment flanges on two sides. These flanges have closed nutplates to allow attachment to the PPS baseplate and PPS side wall. Closed nutplates were used to prevent any metal particles from entering the high voltage section during the bolting operation.

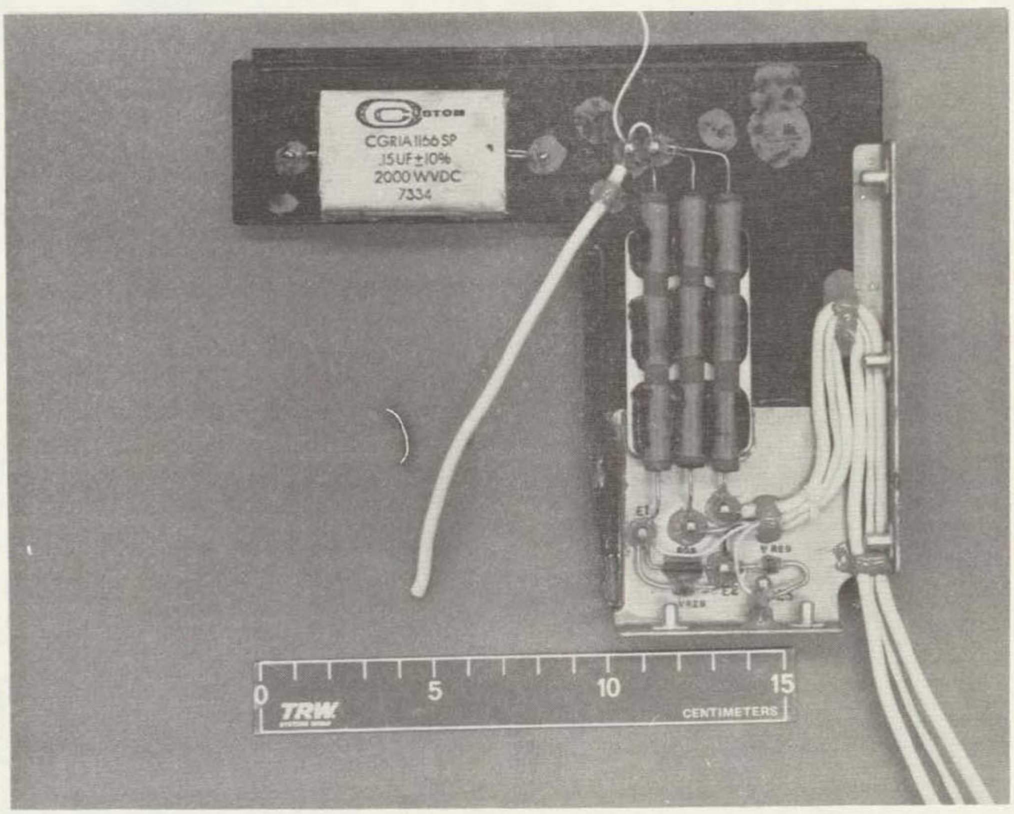


Figure 4-15. Typical High Voltage Circuit Board
Prior to Final Assembly

Three high voltage, high dissipation resistors (center of Figure 4-15), are bonded to a beryllium oxide heat sink using an intermediate casing of polyolefin shrink sleeving to allow for differential thermal expansion. This sleeving was broken into three segments to prevent entrapment of gas. The high voltage reconstituted mica filter capacitor (upper left of Figure 4-15) is bonded to the polymid substrate with a pliant epoxy (Lefkoweld). All high voltage terminations are made with the anticorona spheres discussed previously.

5. PPS PERFORMANCE

A detailed summary of the results of performance testing on all three flight units built is presented in this section. The QF01 unit served as a qualification model and the QF02 and QF03 units are flight units. A list of unit tests is presented prior to the data for each of the three subject units. The last column in the data presentation indicates the test where the worst-case performance was noted.

S/N Test Article QF01 (Qualification Model)

TEST NUMBER AND TEST SEQUENCE

1. Previbration
2. Vibration
3. Postvibration
4H. T/V Hot Temperature
4C. T/V Cold Temperature
4R T/V Room Temperature
5 Final Functional

Worst result out of any one of seven tests listed.

S/N Test Article QF01

Test Requirements	Unit Test Results	Test Number
<u>Commands</u>		
A sequence of commands are given and the required operation of the PPS is verified.	PPS – passed all command tests	1-9
<u>Cathode Heater Supply</u>		
a) Initial set of output current at 100 percent load, room ambient temperature and 27.5 volts on housekeeping bus is to be within 20 mA of customer requirement.	Set point	
Customer requirement 1.290 A	1.294 amps	1
b) DC regulation of output current from initial set point is to be +1 percent for all normal operating conditions of temperature, housekeeping bus voltage, and load.	Maximum deviation from set (+0.494 %) (-0.309 %) (-0.767 %) (0.283 %)	 1 4C
c) AC ripple on output current is to be 1 percent peak to peak maximum for all normal operating conditions of temperature, housekeeping bus voltage, and load.	Maximum ripple 0.164 %	1
d) Voltage telemetry at all full load conditions is to be within 1 percent of initial set at room ambient, 110 percent current at housekeeping bus of 27.5 volts (note measurement accuracy of HTR output voltage ± 3 percent).		
$\frac{V_{TLM}}{V_{OUT}}$ Min = 1.075 $\frac{V_{TLM}}{V_{OUT}}$ Max = 1.165	$\frac{V_{TLM}}{V_{OUT}}$ at minimum 1.100	1
	$\frac{V_{TLM}}{V_{OUT}}$ at maximum 1.120	1

S/N Test Article QF01 (Continued)

Test Requirements	Unit Test Results	Test Number
<u>Ion Pump</u>		
a) With ion pumps 1 and 2 loaded to 10μ, the output must be 3520 volts maximum, 2650 minimum under all normal conditions.	Maximum output 2900 Minimum output 2779	5 4H
b) With one ion pump output shorted, and the other loaded to 10μ, the output must be 2300 minimum under all normal conditions.	Minimum output 2408	4H
<u>Cathode Supply</u>		
a) The output dc voltage must be within ±1 percent of customer requirement over all nominal conditions of load, exp bus voltage and temperature.	Maximum Deviation +0.209 % Maximum Deviation -0.137 %	4H 4C
b) The output ac voltage must be less than 0.01 percent over all nominal conditions.	Max P/P ripple 0.070 %	4H
<u>Collector Supply</u>	<u>Deviation from required value at full RF</u>	
a) The output dc voltage of each output must be within 3 percent at full RF load and 10 percent at zero RF load of the required values. The required values are in 1/10 steps of the customer specified value of cathode voltage. The voltages are all with respect to the cathode potential. The conditions must be met under all nominal conditions of exp bus and temperature.	see below	see below

	Max	Min	Test Number Max	Test Number Min
C2	0.211 %	-0.241 %	3	4C
C3	0.208 %	-0.249 %	3	4C
C4	0.257 %	-0.263 %	3	4C
C5	0.233 %	-0.534 %	3	4C
C6	0.176 %	-0.583 %	3	4C
C7	0.126 %	-0.641 %	3	4C
C8	0.009 %	-0.869 %	3	4C
C9	-0.107 %	-1.950 %	1	4C

S/N Test Article QF01 (Continued)

Test Requirements	Unit Test Results	Test Number
	Deviation from required value at zero RF	
	Under all conditions, the maximum deviation is less than 0.186 percent positive, and the maximum deviation is less than -2.719 percent negative.	
b) The output ac voltage must be less than 2 percent peak to peak under all normal conditions of load, exp bus and temperature. The calculations are with respect to cathode potential.	Max peak to peak ripple	
	C2 0.117	4C
	C3 0.159	4C
	C4 0.156	4C
	C5 0.153	4C
	C6 0.148	4C
	C7 0.169	4C
	C8 0.188	4C
	C9 0.248	4C
Anode Supply		
a) The initial set of output voltage at full load, 27.5 volts housekeeping bus is to be within 20 volts of the customer requirements. Requirement 250.0 volts.	Set 247.06 volts	1
b) DC regulation of output voltage from the initial set point is to be ± 1 percent for all normal operating conditions of temperature, housekeeping bus and load.	Maximum deviation from set	
	+0.004 %	3
	-0.081 %	4H

S/N Test Article QF01 (Continued)

Test Requirements	Unit Test Results	Test Number
c) AC ripple on output voltage is to be ±0.5 percent peak to peak maximum for all nominal conditions of temperature, housekeeping bus and load.	Maximum ripple 0.364 %	1
Power Budget and Efficiency		
a) The power conversion efficiency is 85 percent minimum. This is defined as : $\frac{\text{Power out x 100 percent}}{\text{Power in - Command power - Telemetry power}}$	Efficiency minimum 87.6 %	4H
b) The eclipse power, defined as special instrumentation only. The requirements are undefined	Power maximum 1.157 W	1
c) The eclipse power defined as cathode heater at half power and special instrumentation. The requirements are 9 watts maximum	Power maximum 5.16 W	4C
Protection		
a) Undervoltage requirements are that the PPS must be able to operate from zero to nominal operating voltage without damage.	No destruction voltages from zero to nominal.	
The minimum operating voltage for the housekeeping bus is 26 volts DC	Minimum housekeeping bus 2.03 V for operation	4C
The minimum operating voltage for the exp bus is 65 volts DC	Minimum expected bus 57.1 V for operation	4C
b) Overvoltage requirements are that the PPS must be able to operate from nominal operating voltage to abnormal maximum voltage	The unit was operated at all temperatures at their maximum abnormal voltage	

S/N Test Article QF01 (Continued)

Test Requirements	Unit Test Results	Test Number
Abnormal maximum for housekeeping bus is 36 volts dc		
Abnormal maximum for exp bus is 95 volts dc		
c) Excess body current is defined as 10 mA ± 1 mA for 30 msec ± 20 msec	I_B at shut off maximum deviation from 10 mA is -0.28 mA	4C
	Time at shut off maximum deviation from 30 msec is -13 msec	1
d) Excess ion pump current is defined as 10 μA ± 5 μA	I_{IP} at shut off is within defined limits at all conditions	1-9
<u>Telemetry</u>		
The telemetry channels are divided into four groups to adequately describe its particular accuracy requirement. Note that as part of the tolerance the measurement inaccuracy must be added. These errors are given for each parameter, since they vary depending on the measurement involved.		

S/N Test Article QF01 (Continued)

Test Requirements			Unit Test Results		Test Number	
					Min	Max
a) High Voltage Telemetry The requirement for high voltage telemetry is to have the gain (V_o/V_{TLM}) be within 1 percent of the required value under all conditions.						
Anode	118.6 Min	124.4 Max	121.4 Min	121.8 Max	4R	1
C4	1960 Min	2040 Max	1985 Min	1991 Max	3	1
C5	1960 Min	2040 Max	2001 Min	2007 Max	5	1
C7	1960 Min	2040 Max	1989 Min	1996 Max	5	1
Cathode	2940 Min	3060 Max	3009 Min	3018 Max	4C	1
b) Low Voltage Current Telemetry The requirement for low voltage current telemetry is to have the slope ($\Delta I_o/\Delta TLM$) remain within 1 percent of the initial value found in test 1R over all subsequent conditions.						
I_{76}	2.106 Min	2.192 Max	2.143 Min	2.158 Max	4R	1
$I_{27.5}$	0.317 Min	0.329 Max	0.321 Min	0.325 Max	5	4H
c) High Voltage Current Telemetry The requirement for high voltage current telemetry is to have the slope ($\Delta I_o/\Delta TLM$) remain within 1 percent of the initial value found in test 1R over all subsequent conditions.						
$I_{vac\text{-}Ion}$	1.815 Min	2.455 Max	2.124 Min	2.153 Max	4C	4H
I_{Body}	2.958 Min	3.078 Max	2.963 Min	3.018 Max	3	1

S/N Test Article QF01 (Continued)

Test Requirements			Unit Test Results		Test Number Min	Test Number Max
I_{C1}	2.971 Min	3.098 Max	3.013 Min	3.032 Max	3	1
I_{C2}	2.984 Min	3.106 Max	3.000 Min	3.045 Max	4C	1
I_{C3}	2.975 Min	3.097 Max	3.005 Min	3.036 Max	3	1
I_{C4}	4.957 Min	5.159 Max	4.980 Min	5.058 Max	4C	1
I_{C5}	4.926 Min	5.128 Max	4.959 Min	5.087 Max	4C	4R
I_{C6}	4.967 Min	5.169 Max	4.985 Min	5.072 Max	5	4H
I_{C7}	4.936 Min	5.138 Max	4.989 Min	5.037 Max	3	1
I_{C8}	3.011 Min	3.133 Max	3.012 Min	3.072 Max	5	1
I_{C9}	2.999 Min	3.121 Max	3.009 Min	3.060 Max	3	1
I_{C10}	3.003 Min	3.125 Max	3.004 Min	3.089 Max	4C	5
$I_{CATHODE}$	19.91 Min	20.73 Max	19.93 Min	20.32 Max	4C	1

d) RF Power Telemetry

The requirement of the RF telemetry is that the PPS must amplify a zero to 0.250 volt input signal to an output of zero to 5.00 volts. The tolerance of this gain is ±50 mV at all points of the slope and all temperatures.

Test Requirements	Unit Test Results	Test Number
Forward RF Allowable deviation at zero input, 50 mV maximum	Deviation -0.0016 Max	1
Allowable deviation at 0.125 volt input, 50 mV maximum	Deviation -0.0056 Max	1
Allowable deviation at 0.250 volt input, 50 mV maximum	Deviation -0.0095 Max	1

S/N Test Article QF01 (Continued)

Test Requirements		Unit Test Results	Test Number
Reflected RF	Allowable deviation at zero input, 50 mV maximum	Deviation 0.025 Max	3
	Allowable deviation at 0.125 volt input, 50 mV maximum	Deviation 0.016 Max	3
	Allowable deviation at 0.250 volt input, 50 mV maximum	Deviation 0.021 Max	3

TEST NUMBER AND TEST SEQUENCE

1R. Pre Pot Fab (Room Temperature)

1H. Pre Pot Fab (Hot Temperature)

1C. Pre Pot Fab (Cold Temperature)

2. Post Pot Fab

3. Previbration Functional

4. Vibration

5. Postvibration Functional

6H. T/V 1 (Hot Temperature)

6C. T/V 1 (Cold Temperature)

6R. T/V 1 (Room Temperature)

7. Final Functional 1

8H. T/V 2 (Hot Test)

9. Final Functional 2

S/N Test Article QF02 (Continued)

Test Requirements	Unit Test Results			Test Number	
Ion Pump					
a) With ion pumps 1 and 2 loaded to 10 μ the output must be 3520 volts maximum, 2650 minimum, under all normal conditions.	Maximum output 3326			6C	
	Minimum output 3108			1H	
b) With one ion pump output shorted and the other loaded to 10 μ, the output must be 2300 minimum under all normal conditions.	Minimum output 2623			1H	
Cathode Supply					
a) The output dc voltage must be within ±1 percent of customer requirement over all nominal conditions of load, exp bus voltage and temperature.	Maximum deviation	+0.277 %		1H	
		-0.152 %		6C	
b) The output ac voltage must be less than 0.01 percent over all nominal conditions.	Maximum P/P ripple	0.0098 %		8H	
Collector Supply					
a) The output dc voltage of each output must be within 3 percent at full RF load and 10 percent at zero RF load of the required values. The required values are in 1/10 steps of the customer specified value of cathode voltage. The voltages are all with respect to the cathode potential.	Deviation from required value at full RF				
The conditions must be met under all nominal conditions of exp bus and temperature.		Max	Min	Max	Min
	C2	0.276 %	-0.279 %	1H	6C
	C3	0.255 %	-0.304 %	1H	6C
	C4	0.292 %	-0.333 %	1H	6C
	C5	0.242 %	-0.491 %	1H	6C
	C6	0.181 %	-0.683 %	1H	6C
	C7	0.125 %	-0.723 %	1H	6C
	C8	-0.063 %	-0.906 %	1H	6C
	C9	-0.143 %	-2.643 %	1H	6C

S/N Test Article QF02

Test Requirements	Unit Test Results	Test Number
Commands		
A sequence of commands are given and the required operation of the PPS is verified.	PPS — Passed all command tests	1-9
Cathode Heater Supply		
a) Initial set of output current at 100 percent load, room ambient temperature and 27.5 volts on housekeeping bus is to be within 20 mA of customer requirement.	Set point	
Customer requirement 1.290 A	1.293 Amps	1R
b) DC regulation of output current from initial set point is to be ± 1 percent for all normal operating conditions of temperature, housekeeping bus voltage, and load.	Max deviation from set ($\pm$0.071 -0.766 %	 9
	($\pm$0.706 +0.329 %	9
c) AC ripple on output current is to be 1 percent peak to peak maximum for all normal operating conditions of temperature, housekeeping bus voltage, and load.	Maximum ripple 0.569 %	 3
d) Voltage telemetry at all full load conditions is to be within 1 percent of initial set at room ambient, 110 percent current at housekeeping bus of 27.5 volts (note measurement accuracy of HTR output voltage ± 3 percent).		
$\frac{V_{TLM}}{V_{OUT}}$ Min = 1.153 $\frac{V_{TLM}}{V_{OUT}}$ Max = 1.249	$\frac{V_{TLM}}{V_{OUT}}$ at minimum 1.165	7
	$\frac{V_{TLM}}{V_{OUT}}$ at maximum 1.219	9

S/N Test Article QF02 (Continued)

Test Requirements	Unit Test Results	Test Number
	Deviation from required value at zero RF	
	Under all conditions, the maximum deviation is less than +0.261 percent positive, and the maximum deviation is less than -2.982 percent negative	7 8H
b) The output ac voltage must be less than 2 percent peak to peak under all normal conditions of load, exp bus and temperature. The calculations are with respect to cathode potential.	Max peak to peak ripple	
	C2 0.169	8H
	C3 0.205	8H
	C4 0.236	8H
	C5 0.248	8H
	C6 0.266	8H
	C7 0.271	8H
	C8 0.362	8H
	C9 0.455	8H
Anode Supply		
a) The initial set of output voltage at full load, 27.5 volts housekeeping bus is to be within 20 volts of the customer requirements. Requirement 250.0 volts.	Set 248.34 V	1R
b) DC regulation of output voltage from the initial set point is to be ±1 percent for all normal operating conditions of temperature, housekeeping bus and load.	Maximum deviation from set +0.093 % -0.358 %	1H 6C
c) AC ripple on output voltage is to be ±0.5 percent peak to peak maximum for all nominal conditions of temperature, housekeeping bus and load.	Maximum ripple 0.322 %	5

S/N Test Article QF02 (Continued)

Test Requirements	Unit Test Results	Test Number
Power Budget and Efficiency		
a) The power conversion efficiency is 85 percent minimum. This is defined as: $\frac{\text{Power Out x 100 percent}}{\text{Power In - Command Power - TLM Power}}$	Efficiency minimum 86.9 %	1H
b) The eclipse power, defined as special instrumentation only. The requirements are undefined	Power maximum 1.20 W	1C
c) The eclipse power, defined as cathode heater at half power and special instrumentation. The requirements are 9 watts maximum	Power maximum 5.41 W	1R
Protection		
a) Undervoltage requirements are that the PPS must be able to operate from zero to nominal operating voltage without damage.	No destructive voltages from zero to nominal	
The minimum operating voltage for the housekeeping bus is 26 volts dc	Minimum housekeeping bus for operation 20.6 V	6C
The minimum operating voltage for the exp bus is 65 volts dc	Minimum exp bus for operation 56.4 V	1C
b) Overvoltage requirements are that the PPS must be able to operate from nominal operating voltage to abnormal maximum voltage. Abnormal maximum for housekeeping bus is 36 volts dc. Abnormal maximum for exp bus is 95 volts dc	The unit was operated at all temperatures at their maximum abnormal voltage.	

S/N Test Article QF02 (Continued)

Test Requirements			Unit Test Results		Test Number	
c) Excess body current is defined as 10 mA ± 1 mA for 30 msec ± 20 msec			I_B at shut off maximum deviation from 10 mA is -0.30 mA		8H	
			Time at shut off maximum deviation from 30 msec is -13 msec		1C	
d) Excess ion pump current is defined as 10 µA ± 5 µA			I_{IP} at shut off is within defined limits at all conditions		1-9	
<u>Telemetry</u> The telemetry channels are divided into four groups to adequately describe its particular accuracy requirement. Note that as part of the tolerance the measurement inaccuracy must be added. These errors are given for each parameter, since they vary depending on the measurement involved.						
a) <u>High Voltage Telemetry</u> The requirement for high voltage telemetry is to have the gain (V_o/V_{TLM}) be within 1 percent of the required value under all conditions.					Min	Max
Anode	118.6 Min	124.4 Max	121.1 Min	121.9 Max	6H	1C
C4	1960 Min	2040 Max	1978 Min	1996 Max	7	1C
C5	1960 Min	2040 Max	1988 Min	1996 Max	7	1C
C7	1960 Min	2040 Max	1988 Min	1997 Max	7	1C
Cathode	2940 Min	3060 Max	3016 Min	3030 Max	9	1C

S/N Test Article QF02 (Continued)

Test Requirements			Unit Test Results		Test Number	
b) Low Voltage Current Telemetry The requirement for low voltage current telemetry is to have the slope ($\Delta Io/\Delta TLM$) remain within 1 percent of the initial value found in test 1R over all subsequent conditions.						
I_{76}	2.107 Min	2.193 Max	2.112 Min	2.154 Max	8H	1C
$I_{27.5}$	0.317 Min	0.330 Max	0.321 Min	0.327 Max	1H	6H
c) High Voltage Current Telemetry The requirement for high voltage current telemetry is to have the slope ($\Delta Io/\Delta TLM$) remain within 1 percent of the initial value found in test 1R over all subsequent conditions.					Min	Max
$I_{vac\text{-}Ion}$	1.828 Min	2.473 Max	2.116 Min	2.150 Max	1H	1R
I_{Body}	2.962 Min	3.083 Max	3.022 Min	3.028 Max	7	9
I_{C1}	2.954 Min	3.074 Max	3.013 Min	3.020 Max	7	9
I_{C2}	2.966 Min	3.088 Max	2.967 Min	3.036 Max	3	6H
I_{C3}	4.891 Min	5.091 Max	4.980 Min	5.058 Max	5	6H
I_{C4}	4.949 Min	5.151 Max	4.970 Min	5.050 Max	8H	1R
I_{C5}	4.917 Min	5.118 Max	4.954 Min	5.098 Max	9	1H
I_{C6}	4.880 Min	5.080 Max	4.951 Min	5.058 Max	1H	3
I_{C7}	4.967 Min	5.170 Max	4.969 Min	5.069 Max	5	1R
I_{C8}	7.927 Min	8.251 Max	8.026 Min	8.144 Max	1H	9
I_{C9}	7.921 Min	8.245 Max	8.034 Min	8.225 Max	6R	5
I_{C10}	2.905 Min	3.024 Max	2.964 Min	3.023 Max	1H	6C
$I_{CATHODE}$	19.71 Min	20.51 Max	19.87 Min	20.77 Max	9	1R

S/N Test Article QF02 (Continued)

Test Requirements		Unit Test Results	Test Number
d) RF Power Telemetry The requirement of the RF telemetry is that the PPS must amplify a zero to 0.250 volt input signal to an output of zero to 5.00 volts. The tolerance of this gain is ±50 mV at all points of the slope and all temperatures.			
Forward RF	Allowable deviation at zero input, 50 mV maximum	Deviation +0.024 Max	1C
	Allowable deviation at 0.125 volt input, 50 mV maximum	Deviation +0.018 Max	1H
	Allowable deviation at 0.250 volt input, 50 mV maximum	Deviation +0.021 Max	1H
Reflected RF	Allowable deviation at zero input, 50 mV maximum	Deviation +0.043 max	1H
	Allowable deviation at 0.125 volt input, 50 mV maximum	Deviation +0.041 max	1H
	Allowable deviation at 0.250 volt input, 50 mV maximum	Deviation +0.046 max	1H

S/N Test Article QF03 (Flight Backup Model)

TEST NUMBER AND TEST SEQUENCE

1R. Preconformal Coat (Room Temperature)

2. Previbration Functional Test

3. Vibration

4. Postvibration functional test

5H. T/V Hot Temperature

5C. T/V Cold Temperature

5R. T/V Room Temperature

6. Final Functional Test

S/N Test Article QF03

Test Requirements	Unit Test Results		Test Number
<u>Commands</u>			
A sequence of commands are given and the required operation of the PPS is verified.	PPS — Passed all command tests		<u>1-9</u>
<u>Cathode Heater Supply</u>			
a) Initial set of output current at 100 percent load, room ambient temperature and 27.5 volts on housekeeping bus is to be within 20 mA of customer requirement.	Set point		
Customer requirement <u>1.290</u> A	1.298 Amps		<u>1R</u>
b) DC regulation of output current from initial set point is to be ± 1 percent for all normal operating conditions of temperature, housekeeping bus voltage, and load.	Maximum deviation from set		
	<u>(+0.492 %)</u>	<u>(0.0 %)</u>	<u>5H</u>
	<u>(-0.436 %)</u>	<u>(0.231 %)</u>	<u>6</u>
c) AC ripple on output current is to be 1 percent peak to peak maximum for all normal operating conditions of temperature, housekeeping bus voltage and load.	Maximum ripple	<u>0.591 %</u>	<u>6</u>
d) Voltage telemetry at all full load conditions is to be within 1 percent of initial set at room ambient, 110 percent current at housekeeping. Bus of 27.5 volts (note measurement accuracy of HTR output voltage ± 3 percent)			
$\frac{V_{TLM}}{V_{OUT}}$ Minimum = <u>1.139</u> $\frac{V_{TLM}}{V_{OUT}}$ Maximum = 1.235	$\frac{V_{TLM}}{V_{OUT}}$ at minimum	<u>1.159</u>	<u>2</u>
	$\frac{V_{TLM}}{V_{OUT}}$ at maximum	<u>1.209</u>	<u>1R</u>

S/N Test Article QF03 (Continued)

Test Requirements	Unit Test Results		Test Number
Ion Pump			
a) With ion pumps 1 and 2 loaded to 10 μ the output must be 3520 volts maximum, 2650 minimum under all normal conditions.	Maximum output 3348		5C
	Minimum output 3186		5H
b) With one ion pump output shorted, and the other loaded to 10 μ, the output must be 2300 minimum under all normal conditions.	Minimum output 2690		5H
Cathode Supply			
a) The output dc voltage must be within ±1 percent of customer requirement over all nominal conditions of load, exp bus voltage and temperature.	Maximum deviation	+0.251 %	4
		-0.098 %	5C
b) The output ac voltage must be less than 0.01 percent over all nominal conditions.	Maximum P/P ripple	0.0063 %	5R

Test Requirements	Deviation from required value at full RF			Test Number	
Collector Supply		Max	Min	Max	Min
a) The output dc voltage of each output must be within 3 percent at full RF load and 10 percent at zero RF load of the required values. The required values are in 1/10 steps of the customer specified value of cathode voltage. The voltages are all with respect to the cathode potential.	C2	0.261 %	-0.193 %	4	5C
	C3	0.264 %	-0.207 %	4	5C
	C4	0.291 %	-0.225 %	4	5C
	C5	0.265 %	-0.326 %	2	5C
The conditions must be met under all nominal conditions of exp bus and temperature.	C6	0.214 %	-0.570 %	2	5C
	C7	0.137 %	-0.595 %	2	5C
	C8	-0.026 %	-0.782 %	4	5C
	C9	-0.053 %	-1.966 %	4	5C

S/N Test Article QF03 (Continued)

Test Requirements	Unit Test Results	Test Number
	Deviation from required value at zero RF Under all conditions, the maximum deviation is less than 0.280 percent positive, and the maximum deviation is less than -2.214 percent negative	
b) The output ac voltage must be less than 2 percent peak to peak under all normal conditions of load, exp bus and temperature. The calculations are with respect to cathode potential.	Max peak to peak ripple	
	C2 0.167	5R
	C3 0.189	5H
	C4 0.238	2
	C5 0.230	5H
	C6 0.411	5H
	C7 0.265	5H
	C8 0.308	5H
	C9 0.304	5H
Anode Supply		
a) The initial set of output voltage at full load, 27.5 volts housekeeping bus is to be within 20 volts of the customer requirements. Requirement 250.0 volts.	Set 246.68 V	1R
b) DC regulation of output voltage from the initial set point is to be ± 1 percent for all normal operating conditions of temperature, housekeeping bus and load.	Max deviation from set +0.072 %	5C
	-0.085 %	5H
c) AC ripple on output voltage is to be ± 0.5 percent peak to peak maximum for all nominal conditions of temperature, housekeeping bus and load.	Max ripple 0.486 %	4

S/N Test Article QF03 (Continued)

Test Requirements	Unit Test Results	Test Number
Power Budget and Efficiency		
a) The power conversion efficiency is 85 percent minimum. This is defined as: $$\frac{\text{Power Out x 100 percent}}{\text{Power In - Command Power - TLM Power}}$$	Efficiency minimum 87.0 %	5H
b) The eclipse power, defined as special instrumentation only. The requirements are undefined	Power maximum 1.15 W	1R
c) The eclipse power, defined as cathode heater at half power and special instrumentation. The requirements are 9 watts maximum	Power maximum 5.43 W	1R
Protection		
a) Undervoltage requirements are that the PPS must be able to operate from zero to nominal operating voltage without damage	No destructive voltages from zero to nominal	
The minimum operating voltage for the housekeeping bus is 26 volts dc	Minimum housekeeping bus for operation 19.7 V	5C
The minimum operating voltage for the exp bus is 65 volts dc	Min exp bus for operation 55.6 V	5C
b) Overvoltage requirements are that the PPS must be able to operate from nominal operating voltage to abnormal maximum voltage. Abnormal maximum for housekeeping bus is 36 volts dc. Abnormal maximum for exp bus is 95 volts dc	The unit was operated at all temperatures at their maximum abnormal voltage	

S/N Test Article QF03 (Continued)

Test Requirements	Unit Test Results	Test Number
c) Excess body current is defined as 10 mA ±1 mA for 30 msec ±20 msec	I_B at shut off maximum deviation from 10 mA is -0.27 mA	5H
	Time at shut off maximum deviation from 30 msec is -13 msec	1R
d) Excess ion pump current is defined as 10 µA ±5 µA	I_{IP} at shut off is within defined limits at all conditions	1-9
Telemetry		
The telemetry channels are divided into four groups to adequately describe its particular accuracy requirement. Note that as part of the tolerance the measurement inaccuracy must be added. These errors are given for each parameter, since they vary depending on the measurement involved.		
a) High Voltage Telemetry		Min Max
The requirement for high voltage telemetry is to have the gain (Vo/V_{TLM}) to be within 1 percent of the required value under all conditions.		
Anode 118.6 Min 124.4 Max	121.0 Min 121.1 Max	6 5H
C4 1960 Min 2040 Max	1985 Min 1986 Max	5R 6
C5 1960 Min 2040 Max	1976 Min 1978 Max	5R 1R
C7 1960 Min 2040 Max	1993 Min 1995 Max	5R 6
Cathode 2940 Min 3060 Max	3014 Min 3019 Max	5R 2
b) Low Voltage Current Telemetry		
The requirement for low voltage current telemetry is to have the slope ($\Delta Io/\Delta TLM$) remain within 1 percent of the initial value found in test 1R over all subsequent conditions.		

S/N Test Article QF03 (Continued)

Test Requirements			Unit Test Results		Test Number	
I_{76}	2.1217 Min	2.2083 Max	2.161 Min	2.169 Max	5H	5C
$I_{27.5}$	0.3184 Min	0.3314 Max	0.324 Min	0.325 Max	5H	6
c) High Voltage Current Telemetry						
The requirement for high voltage current telemetry is to have the slope ($\Delta Io/\Delta TLM$) remain within 1 percent of the initial value found in test 1R overall subsequent conditions.					Min	Max
$I_{vac\text{-}Ion}$	2.097 Min	2.184 Max	2.136 Min	2.171 Max	5H	5R
I_{Body}	2.948 Min	3.076 Max	3.006 Min	3.011 Max	4	6
I_{C1}	2.971 Min	3.093 Max	3.032 Min	3.035 Max	4	6
I_{C2}	2.954 Min	3.075 Max	2.956 Min	3.029 Max	5C	5H
I_{C3}	4.885 Min	5.085 Max	4.981 Min	5.016 Max	4	5H
I_{C4}	4.880 Min	5.079 Max	4.921 Min	4.985 Max	6	5R
I_{C5}	4.860 Min	5.059 Max	4.946 Min	4.993 Max	5R	6
I_{C6}	4.872 Min	5.069 Max	4.966 Min	5.013 Max	1R	5H
I_{C7}	4.854 Min	5.051 Max	4.957 Min	4.990 Max	1R	5C
I_{C8}	7.875 Min	8.193 Max	8.022 Min	8.124 Max	6	5H
I_{C9}	7.901 Min	8.224 Max	8.063 Min	8.097 Max	2	5H
I_{C10}	2.958 Min	3.080 Max	2.982 Min	3.032 Max	6	4
$I_{CATHODE}$	19.66 Min	20.47 Max	19.86 Min	20.09 Max	5C	4

S/N Test Article QF03 (Continued)

Test Requirements	Unit Test Results	Test Number
d) RF Power Telemetry The requirements of the RF telemetry is that the PPS must amplify a zero to 0.250 volt input signal to an output of zero to 5.00 volts. The tolerance of this gain is ±50 mV at all points of the slope and all temperatures.		
Forward RF Allowable deviation at zero input, 50 mV maximum	Deviation 0.016 Max	4
Allowable deviation at 0.125 volt input, 50 mV maximum	Deviation 0.025 Max	2
Allowable deviation at 0.250 volt input, 50 mV maximum	Deviation 0.027 Max	2
Reflected RF Allowable deviation at zero input, 50 mV maximum	Deviation 0.018 Max	4
Allowable deviation at 0.125 volt input, 50 mV maximum	Deviation 0.019 Max	2
Allowable deviation at 0.250 volt input, 50 mV maximum	Deviation 0.026 Max	4

6. TEP VARIABLE CONDUCTANCE HEAT PIPE SYSTEM

6.1 INTRODUCTION

This section describes the design, fabrication, and testing of the transmitter experiment package (TEP) variable conductance heat system (VCHPS). The VCHPS provides thermal control of the TEP, along with the South Panel radiator on the Communications Technology Satellite (CTS).

The VCHPS consists of three gas loaded, variable conductance heat pipes, a space radiator and supporting structure. The heat pipes thermally connect the TEP baseplate with the space radiator which is mounted to the CTS directly above the spacecraft's South Panel (Figure 6-1). The heat pipe radiator rejects the waste heat from the TEP power processor and traveling-wave-tube output stage. The waste heat is transmitted to the radiator through the heat pipes. The variable conductance feature of the VCHPS allows the space radiator to be thermally disconnected from the TEP baseplate during TEP power-down conditions. The effective thermal conductance between the baseplate and radiator is varied over a ratio of approximately 1100:1 depending on heat pipe evaporator temperature.

The subsequent sections of this report will describe in detail the design, fabrication and testing aspects of the VCHPS.

6.2 SUMMARY

The VCHPS is designed to provide a heat rejection capability of 196 watts at a 50°C (122°F) evaporator saddle temperature under maximum design conditions (summer solstice) with any two of the three heat pipes operational. The predicted system performance for any combination of heat pipes operating is shown in Table 6-1. As shown, the minimum heat rejection occurs for the situation where the outboard heat pipe has failed, although the other two cases of single heat pipe failure are not significantly different from the outboard heat pipe failed case.

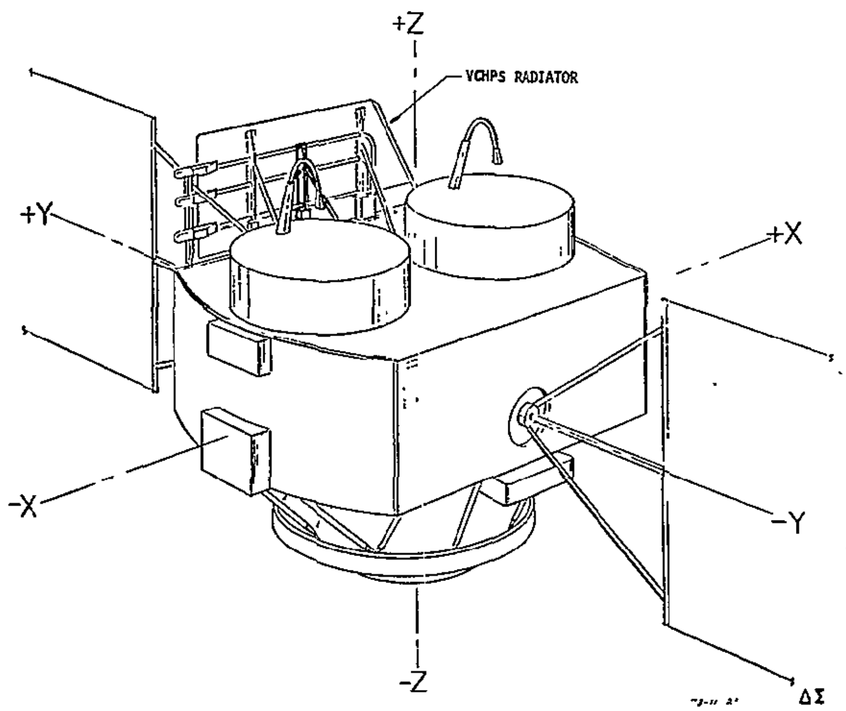


Figure 6-1. CTS Spacecraft

The heat pipes are designed to operate over a control range of 21°C (70°F) to 48°C (118°F) which maintains the evaporator saddle below 50°C (122°F) for the design power dissipation of 196 watts. The heat pipe non-condensible gas inventories are such that the heat pipes turn-on sequentially (inboard to outboard) at approximately 3°C intervals. This staggering of the heat pipe turn-on points also ensures that at maximum load conditions each heat pipe carries a load proportional to its load carrying capability.

The individual heat pipe load carrying capacities as determined in one-g testing are shown in Table 6-2. The SN006 set of heat pipes have been designated the life test set and, as such, were not assembled with a radiator. The SN005 set of heat pipes has been designated the primary flight unit with the SN004 set as the flight backup system.

Table 6-1. CTS Variable Conductance Heat Pipe System Performance Summer Solstice

Saddle Temp. °C	Heat Pipe Failed	System Heat Rejection (Watts)	System Margin** (%)
48	None	219	40
50	Inboard (#1)	198	27
49	Middle (#2)	197	26
50	Outboard (#3)	196	25

**Based on expected load of 156 watts

Table 6-2. TEP Heat Pipe Performance

ASSEMBLY	HEAT PIPE NO./CAPACITY (WATTS)		
	-1	-2	-3
001	175	175	155
002	165	155	165
004	185	125	165
005	165	145	165
006	165	125	155

6.3 VCHPS DESCRIPTION

This section presents a discussion of the design requirements, a general system description and the assembly to assembly variations.

6.3.1 Design Requirements

The VCHPS design requirements are specified by the Interface Control Document (Reference 1). The major design requirements will be discussed herein including those which were either modified or added subsequent to revision A of the ICD. The design requirements can be classified as thermal, mechanical or materials.

6.3.1.1 Thermal Requirements

The thermal requirements are the system heat rejection capability, the control temperature range and the thermal characteristics of the structure and component surfaces. The system heat rejection capability requirements are referenced to the heat pipe assembly evaporator saddle rather than the TEP baseplate (the item being thermally controlled). The heat pipe evaporator saddle is selected as the reference point because the temperature of the TEP baseplate is controlled by other heat transfer mechanisms in addition to the VCHPS (e.g., south panel radiator surface).

The heat rejection capability of the VCHPS shall be 196 watts or greater under maximum sink conditions whenever the evaporator saddle is at or above 50°C (122°F). The VCHPS shall meet this requirement with any two of the three heat pipes operating for up to 3 years. The system shall rediate no more than 3 watts whenever the evaporator saddle is 10°C (50°F) or less.

The heat pipe capacity for any two heat pipes operating shall be 300 watts or more for a 50°C (122°F) saddle temperature when the radiator heat rejection is 196 watts (maximum sink conditions).

The temperature control range for the VCHPS shall be between an evaporator saddle temperature of 21°C (70°F) for all heat pipes off and 50°C (122°F) for the system full on.

Other thermal requirements such as structure surface properties and design environmental conditions shall be as specified in the ICD (Reference 1).

6.3.1.2 Mechanical Requirements

The mechanical design requirements consist basically of physical, interface and weight constraints as well as the design loads. This section of the report will discuss those design requirements which had the most significant effect on the mechanical design of the VCHPS. For a complete review of the mechanical design requirements the reader is directed to the ICD (Reference 1).

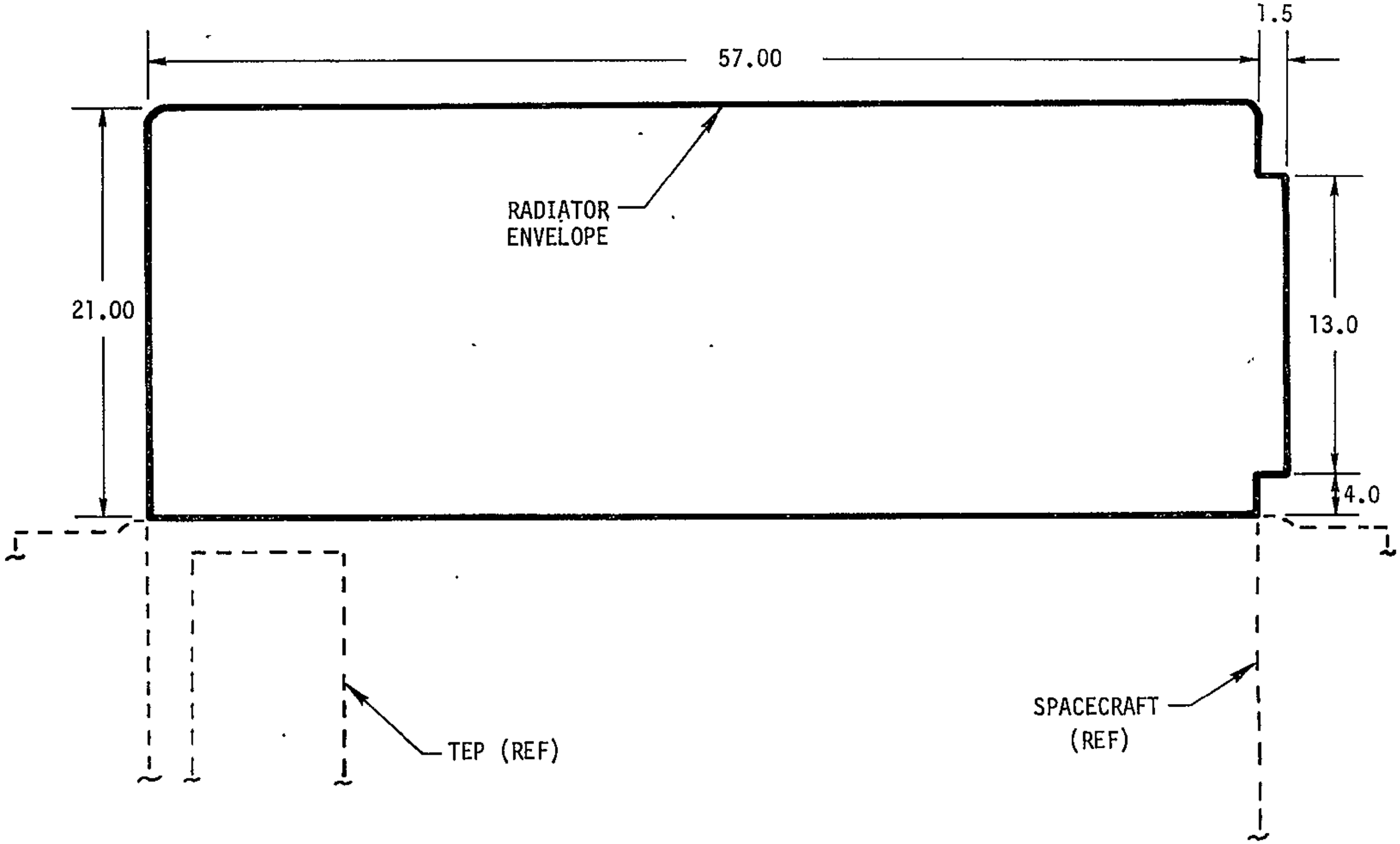
The physical constraint most influential on the design is the allowable radiator fin envelope. The radiator shall fit within the envelope shown in Figure 6-2. This allowable envelope is a change to the ICD (Reference 1).

The VCHPS interfaces structurally with the CTS South Panel and Forward Platform of the spacecraft. The VCHPS shall be designed such that the South Panel loads shall not be transmitted to the Forward Platform and/or Forward Thrust Tube via the VCHPS radiator structure. The only loads to be reacted at the Forward Platform are those associated with the radiator mass. The radiator and associated support structure shall mount to the South Panel at no more than five points and to the Forward Platform at no more than three points. This mounting interface requirement is a change that resulted from the preliminary design review and was approved at the critical design review (References 2 and 3).

The VCHPS radiator design is to allow detachment of the radiator from the heat pipe subassembly without requiring recharging of heat pipes. The radiator shall be capable of being detached or replaced on the support structure while the VCHPS is installed on the spacecraft.

The mechanical environments which the VCHPS must withstand are shown in Table 6-3. The margin of safety under these loadings shall be 1.0 or greater. In addition, the VCHPS radiator structure shall have a first mode natural frequency greater than 20 Hz. It shall be a design goal to produce a natural frequency between 25 and 35 Hz.

The VCHPS shall not weigh more than 16.3 ± 0.2 pounds at launch. This represents a change from the initial weight requirement in the last revision of the ICD (15.9 pounds maximum).



NOTE: DIMENSIONS = IN INCHES

75-23

Figure 6-2. Radiator Fin Envelope

Table 6-3. VCHPS Mechanical Environments

ENVIRONMENT	CRITERIA	REMARKS
Ultimate load	75g in any axis	F.S. $\geq$ 1.0
Yield load	60g in any axis	F.S. $\geq$ 1.0
Sinusoidal Vibration	Withstand levels in Table 3a	
Random Vibration	$0.045g^2/Hz$ for $20 \leq f \leq 2000$ Hz at 2 minutes per axis	
Acoustic	Withstand loading in Table 3b for one minute per level	
Acceleration	Spacecraft centrifugal loads of 132 rpm during ground tests	See ICD for additional requirements
Aerodynamic	No requirements	

Table 6-3a. Vibration — Sinusoidal

Z (THRUST) AXIS*	
FREQUENCY (Hz)	ACCELERATION g's (0-P)
5 - 25	0.5" DA Slope to 16.0
25 -70	16.0
70 - 2000	5.0
Y (NORMAL TO PANEL) AXIS*	
FREQUENCY (Hz)	ACCELERATION g's (0-P)
5 - 15	0.5" DA Slope to 6.0
15-- 40	6.0
40 - 100	10.0
100 - 2000	5.0
- X (ALONG PANEL) AXIS*	
FREQUENCY (Hz)	ACCELERATION g's (0-P)
5 - 15	0.5" DA Slope to 5.0
15 - 2000	5.0

*Sweep Rate: 2 Oct/Min

Table 6-3b. Acoustic Spectrum

FREQUENCY (Hz)	SOUND PRESSURE LEVEL -dB (REF 0002 DYNES/CM^2)
375 - 75	130
75 - 150	135
150 - 300	138
300 - 600	140
600 - 1200	141
1200 - 2400	138
2400 - 4800	134
4800 - 9600	129
OVERALL	146

6.3.1.3 Materials Requirements

The primary design requirement dealing with materials is concerned with grounding of metallic coated films. The multilayer insulation (vacuum deposited aluminum films) shall be grounded to the spacecraft. The silvered Teflon shall be applied such that no single area exceeds 200 cm^2 (31 in^2). The grounding requirements were imposed following the critical design review. Other materials design requirements are detailed in the ICD (Reference 1).

6.3.2 Subsystem Description

This section of the report presents a general description of the VCHPS and its major subassemblies. A detailed description of the system can be obtained from the drawings (not included in this report) listed in Table 6-4. The assembly of the VCHPS with the spacecraft is detailed on drawing 315257.

This section of the report will describe the basic VCHPS in the flight configuration. The differences between flight and engineering models will be noted throughout the description. The engineering models are serial numbers (SN) 001 and 002 with the flight models being SN004 (backup unit) and SN005 (primary unit). The SN006 unit is slated for heat pipe life testing and, as such, consists of the heat pipe subassembly (D315259) without a readiator or supporting structure. The SN003 heat pipe assembly was deleted from the program prior to initating heat pipe fabrication.

6.3.2.1 Heat Pipes

The VCHPS heat pipes are noncondensible gas controlled heat pipes to provide variable thermal conductance between the TEP and the VCHPS radiator. The noncondensible gas (10% Helium, 90% Nitrogen) provides variable control of the heat transport to the radiator as shown in Figure 6-3. The vapor pressure in the evaporator which is established by the evaporator temperature (vapor pressure versus temperature of saturated fluid relationship) determines the vapor-gas front position for a given reservoir temperature. As the evaporator temperature varies according to energy input, the vapor-gas front position varies and increases (or decreases) the available area. Thus, the heat rejection from the radiator is matched with the energy being transported through the heat pipes and/or support structure. For the TEP VCHPS this corresponds to the maximum capability under full-on conditions or the parasitic heat leak under full-off conditions.

Table 6-4. VCHPS Detail Drawings

INDENTURED DRAWING LIST	
• 315257	S/C Instl, TEP/VCHP
• D315266	Strut Assy, Radiator
• D315267	Insulation Installation
• D315258	VCHP/RAD, Assembly
• D315265	Radiator Assembly
• D315259	Heat Pipe Subsys. Assy
• D315260	Heat Pipe Assy
• D315261	Cap-Reservoir
• D315262	Wick-Reservoir
• D315263	Wick-Tube
• D315264	Tube-Heat Pipe
• D315272	Terminal Board-Temperature Transducer
• D315273	Connector Bracket
• D315277	Protective Cover
ANCILLARY HARDWARE	
D315271	Heat Pipe Simulator
T315276	Hoist Fixture - Heat Pipe System
T315275	Hoist Fixture - Transmitter Experiment Package

Two methods of heat pipe control are shown in Figure 6-3; cold reservoir (variable temperature) and heated reservoir (constant temperature). The heated reservoir method will provide a narrow temperature control band whereas the cold reservoir method usually results in a much wider control band depending on the range of sink conditions available to the reservoir. Since the VCHPS temperature control range requirement is relatively broad (approximately 40°C, 72°F), the simpler cold reservoir control method is used for heat pipe control.

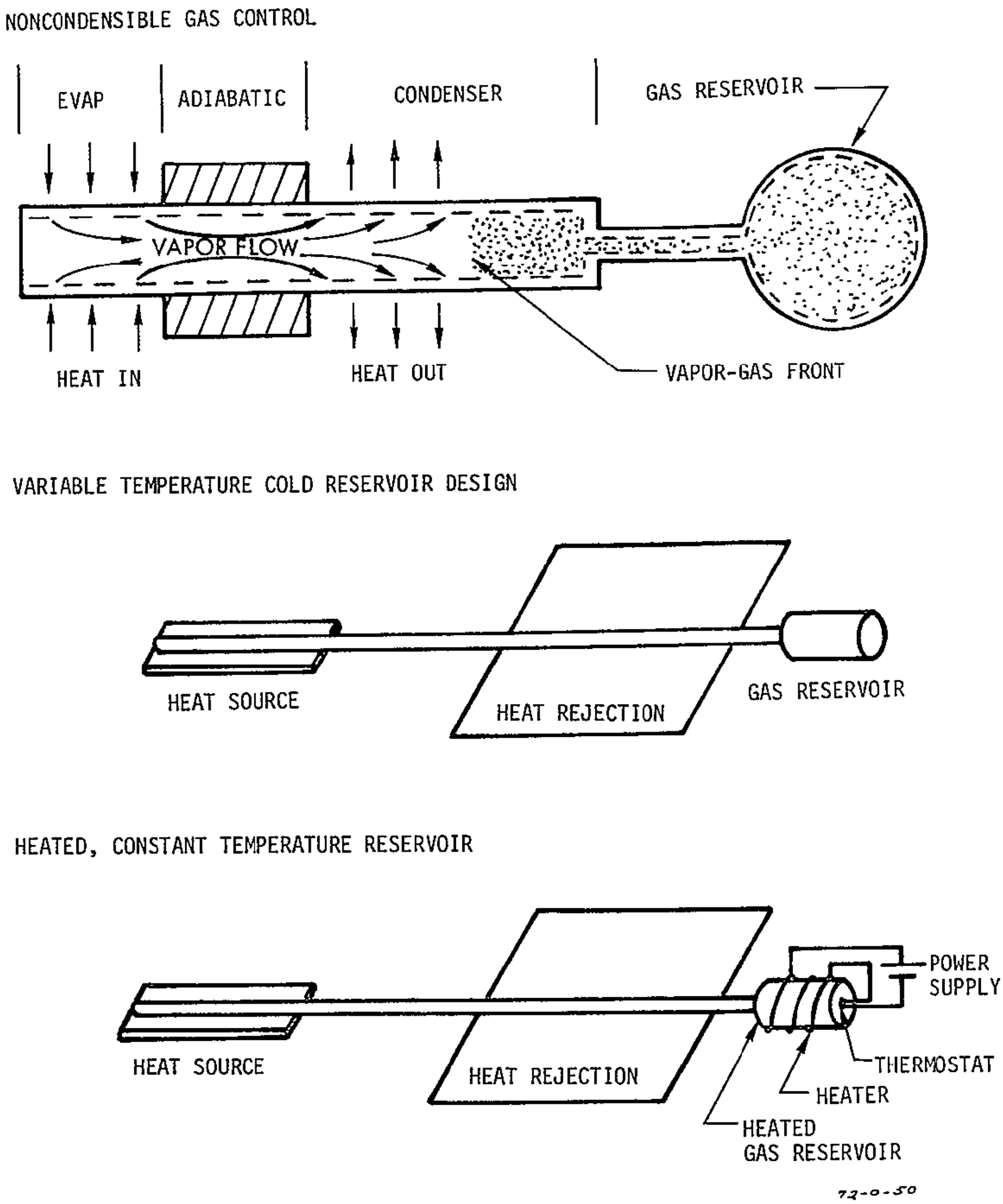


Figure 6-3. Heat Pipe Control Schemes

The heat pipe design must consider a number of parameters which may vary from application to application. The more important parameters are shown in Table 6-5. The heat transfer requirements are very important since they influence the choice of wick configuration, working fluid, tube material and tube size that can be used. The choice of wick configuration is dictated by the magnitude of the product of heat transfer rate required and the effective transport distance ($\dot{q}\ L_{eff}$). Since the TEP application requires a wick capable of approximately 7200 watt-inches ($\dot{q}\ L_{eff}$ = 7200 watt-inches) which must be tested in a one-gee environment, the wick configuration shown in Figure 6-4 was selected. This wick configuration is an arterial wick and consists of a diametral, homogeneous, metal felt wick with two wire mesh arteries. The wire mesh arteries provide for axial fluid return to the evaporator with minimum pressure drop while the metal felt wick provides liquid communication between the fluid in the arteries and the evaporator and condenser surfaces.

To reliably operate a wick configuration of this type at the required $\dot{q}\ L_{eff}$ levels, the arteries must be filled with liquid (primed) at all times. Should a noncondensible gas bubble be entrained in the artery, the maximum equivalent heat transport of the artery is greatly reduced. Accordingly, a method for removal of the entrained gas bubble(s) is required and the method used in the VCHPS heat pipes is shown in Figure 6-5.

The priming foil which is attached at the evaporator end of the artery acts as a priming aid by allowing gases entrained in the arteries to be vented during priming. The holes in the priming foil and the priming foil thickness are sized so as to force menisci coalescence of fluid plugged holes in the region of a gas bubble. This removal of the fluid film bridging the hole allows the entrained gas to be vented from the artery. Thus, gas bubbles entrained in the artery are swept to the evaporator by liquid returning from the condenser while the thermal load is building up in the heat pipe. The bubbles are vented from the artery which results in a fully primed artery when maximum thermal load is achieved.

Table 6-5. Heat Pipe Design Considerations

OBJECTIVE:

TO MEET CAPACITY AND CONTROL REQUIREMENTS WITH A MINIMUM WEIGHT, MAXIMUM RELIABILITY, MINIMUM SYSTEM CONSTRAINT DESIGN

- HEAT TRANSFER
  - TUBE DIAMETER, MATERIAL AND THICKNESS
  - WICK DESIGN
  - WORKING FLUID
  - BODY FORCE FIELDS
  - CONTROL SCHEME (RESERVOIR CONDITIONS)
- 1-G TESTING
  - SYSTEM GEOMETRY
  - WICK DESIGN
  - WORKING FLUID
- SPACE OPERATION
  - FLUID INVENTORY CONTROL
  - LIFE (MATERIALS COMPATIBILITY)
- MECHANICAL DESIGN
  - FABRICABILITY
  - PRESSURE VESSEL DESIGN
  - VIBRATION

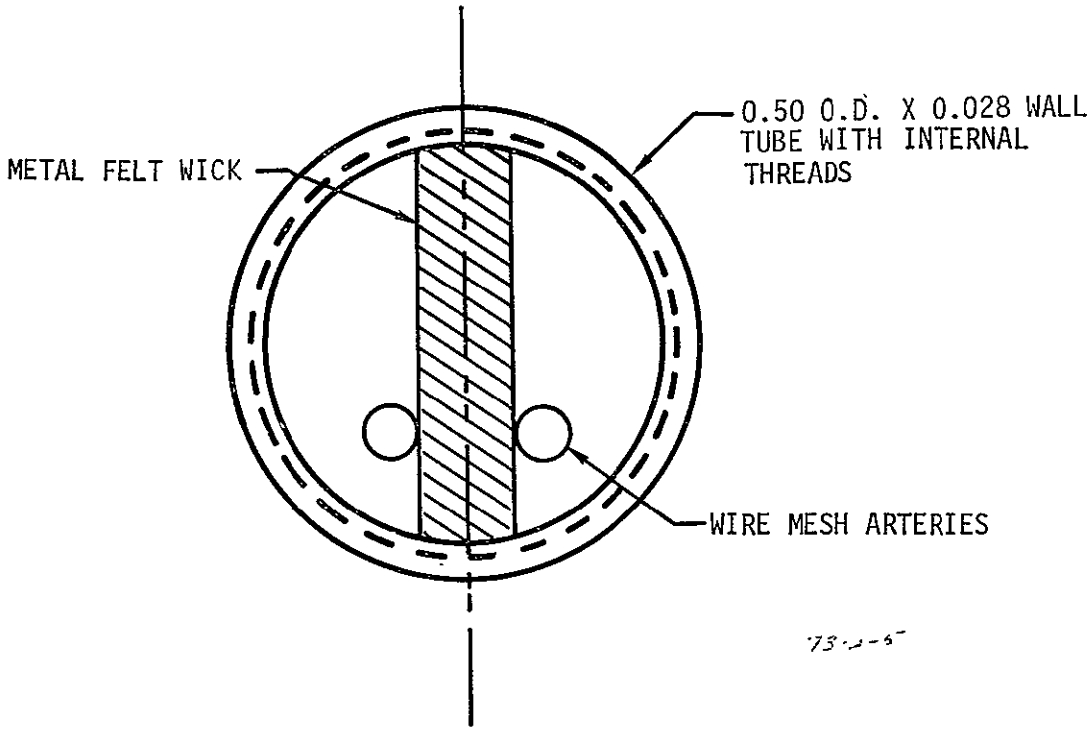


Figure 6-4. TEP Heat Pipe Wick Configuration

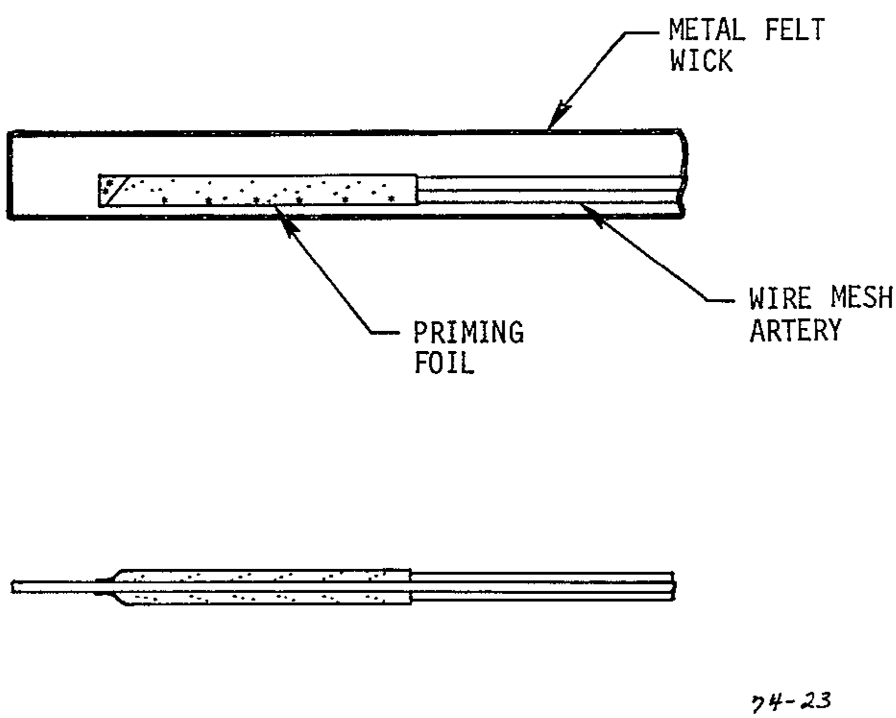


Figure 6-5. TEP Heat Pipe Wick Assembly

The choice of working fluid is dictated by a number of factors as shown in Table 6-5. However, for the TEP application, methanol was chosen because of its relatively low vapor pressure and its low freezing point (-97°C; -143°F). The low vapor pressure is required for the use of arteries to eliminate pressure fluctuation initiated arterial depriming which has been a problem in arterial/ammonia systems. At the time of design decision, a non-arterial ammonia heat pipe that had the necessary thermal transport capability was not available hence an arterial wick configuration was required.

The heat pipe tube is a one-half inch out-side diameter, 304 stainless steel tube with a 28 mil wall as shown in Table 6-6. The choice of 304 stainless steel was again a result of materials compatibility with methanol. The tube is threaded on the interior at 100 threads per inch as shown in Figure 6-4 to promote heat transfer at minimum temperature drop. By providing internal grooves (threads), heat transfer to the liquid surface is through the metal bands between grooves rather than through a liquid film. Thus, the relatively high thermal conductivity of the metal rather than that of the liquid establishes the temperature drop at any given heat transfer rate.

The heat pipe tubes with internal wicks and their associated reservoirs make up a heat pipe assembly as shown in Figure 6-6. The reservoir on each heat pipe serves two purposes. The primary purpose is to provide the necessary volume of non-condensible gas for the control aspects of the heat pipes. In addition to control gas containment, the reservoirs provide a location for excess fluid to reside during normal heat pipe operation. Since the requirement for the heat pipes to be able to reprime near the freezing point of methanol sets the fluid inventory, excess fluid occurs which cannot be totally contained in the natural reservoirs formed by the heat pipe wick/artery/tube wall geometry.

Table 6-6. Heat Pipe Design Details

TUBES:	304 stainless steel, .500 O.D. x .028 wall, internally threaded with 100 TPI, .005 deep, 40° included angle grooves.
RESERVOIRS:	304 stainless steel, spun hemispherical cap with 1.75 O.D. cylindrical center section. Reservoir to condenser volume ratio varies from 1.5 to 2.0.
WICKS:	Reservoir: 304 stainless steel metal felt, .020 thick, spot welded to interior walls.
	Tube: 304 stainless steel metal felt, .050 thick, interference fit across diameter of tube.
	Arteries: 150 mesh 316 stainless steel screen formed and welded to .063 I.D. tubes and spot welded to diametral wick.
	Priming Foils. .0005 thick 304 stainless steel foil with .010 holes, formed and welded to .063 I.D. tubes and spot welded to ends of arteries and diametral wick.
SADDLES:	6061 aluminum alloy extrusion soldered to tubes.
WORKING FLUID:	Methanol, spectrophotometric grade.
CONTROL GAS:	90% nitrogen, 10% helium, research grade.

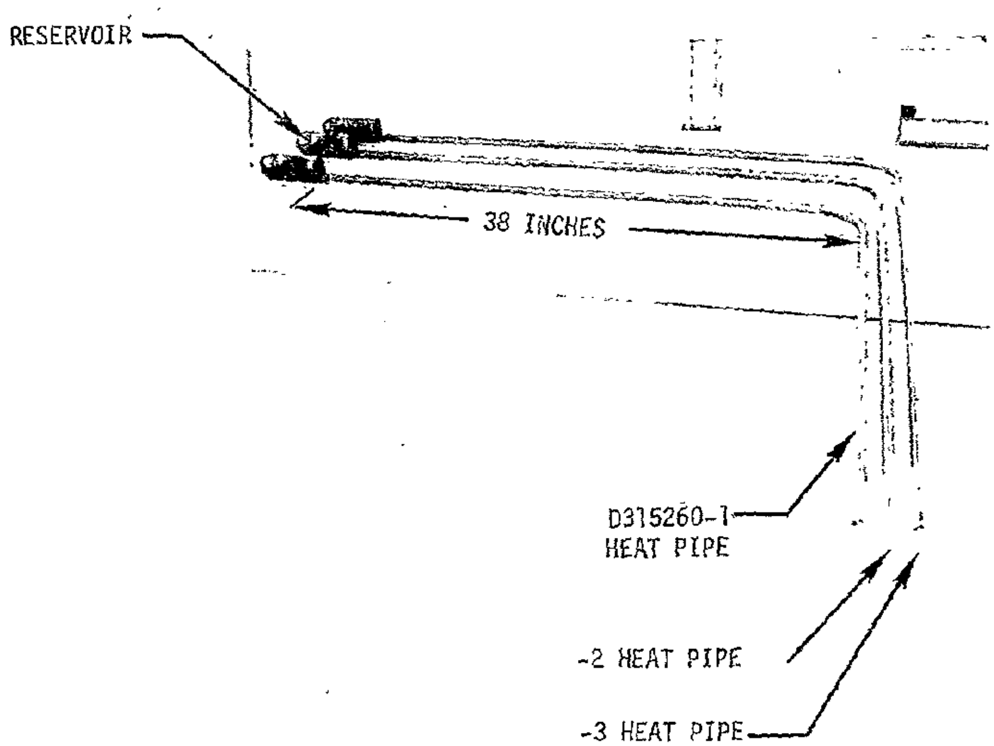


Figure 6-6. VCHPS Heat Pipes

6.3.2.2 Heat Pipe Subassembly

The heat pipe subassembly consists of the three heat pipes, condenser and evaporator saddles, and the heat pipe simulator tube as shown in Figure 6-7. The heat pipes and simulator tube are soldered into the aluminum saddles to form the heat pipe subassembly. The use of solder rather than mechanical means to attach the heat pipes to the saddles provides for better heat transfer across the joint, and, thus, minimizes the temperature drop associated with this attachment interface. The lower evaporator saddle provides for attachment of VCHPS to the TEP baseplate and the upper saddle provides a mounting location for the output stage of the traveling-wave-tube (OST) of the TEP.

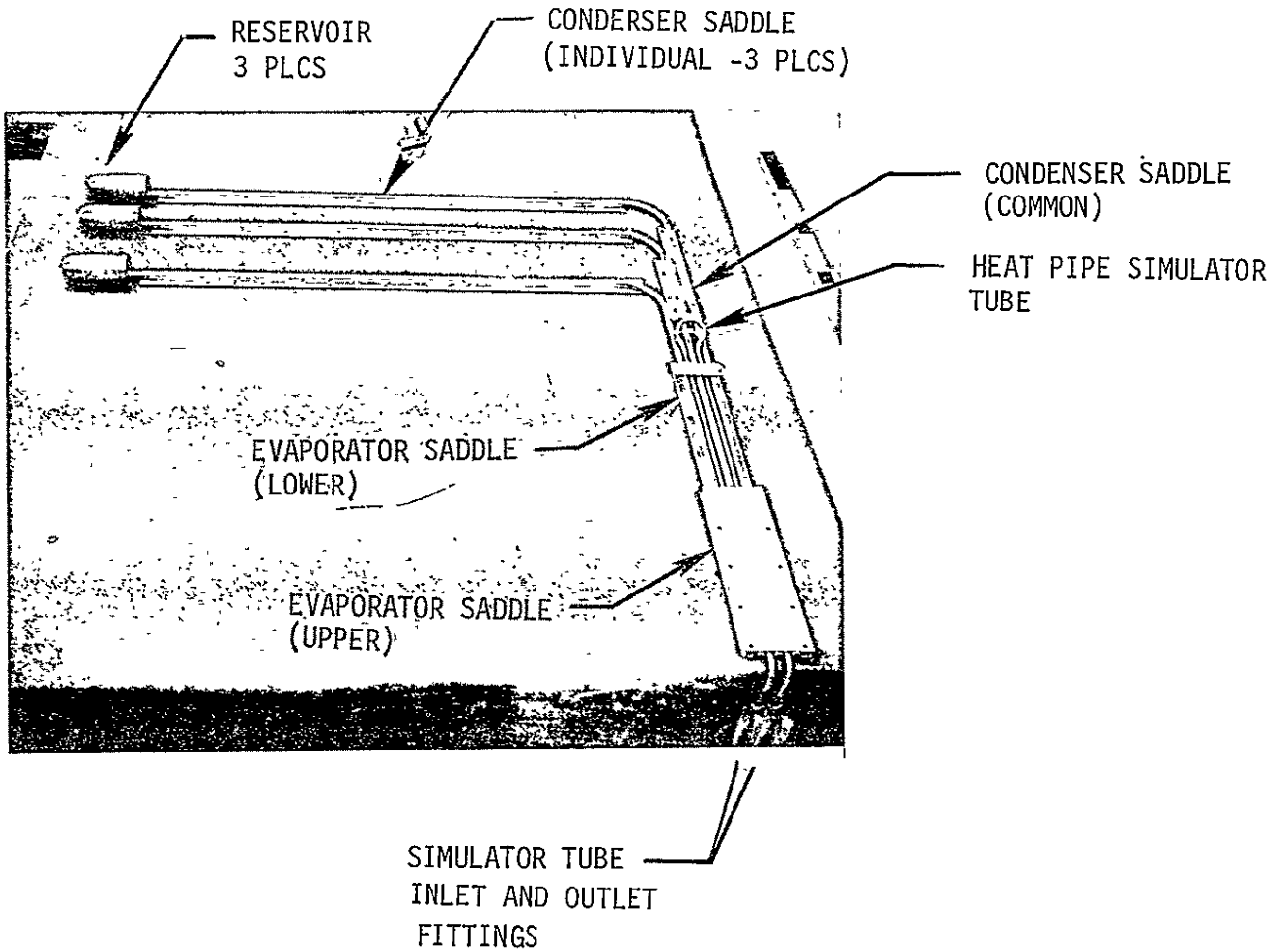


Figure 6-7. VCHPS Heat Pipe Subassembly

The condenser saddles provide the means for attaching the heat pipe subassembly to the radiator. From the heat transfer aspects of the system, it would be desirable to have the condenser saddles as an integral part of the radiator. However, the requirement for radiator removal precludes integral saddles and leads to the use of threaded fasteners to attach the radiator to the condenser saddles. All interfaces of the heat pipe subassembly that mechanically attach to either the TEP or radiator are coated with RTV566 to provide good heat transfer across the interface in the orbital vacuum environment.

The heat pipe simulator tube is included in the assembly for one-gee test purposes. During spacecraft testing and/or checkout there are orientations where the heat pipes cannot operate (evaporator at higher elevation relative to condenser) and an auxiliary cooling system must be provided. The simulator tube is equipped with AN fittings on the inlet and outlet for connecting to an auxiliary cooling system. Thus, if it is necessary to operate the TEP when the heat pipes are inoperable because of spacecraft altitude, a coolant can be circulated through the simulator tube for removal of TEP waste heat. The fittings can then be cut off after the last use of the simulator tube to reduce the launch weight of the VCHPS.

6.3.2.3 VCHPS Assembly

The VCHPS consists of the heat pipe subassembly, a radiator and associated support structure and thermal insulation. The total assembly is shown in Figure 6-8. The radiator is sized to reject the design heat load under maximum design conditions. The radiator, heat pipes and saddles exterior to spacecraft, and tees are coated with silvered Teflon tape (Schjeldohl Thermal Control, G404300) to provide a low solar absorptance to emittance ratio (α_s/ϵ) which minimizes the effects of isolation on radiator heat rejection capability. The initial α_s is 0.09, however, due to the deleterious effects of charged particle bombardment and ultraviolet irradiation associated with a synchronous orbit, the solar absorptivity can degrade to approximately 0.20 after 2 years exposure. The radiator will have higher system heat rejection capability at the beginning than at the end of the mission because of the change in α_s.

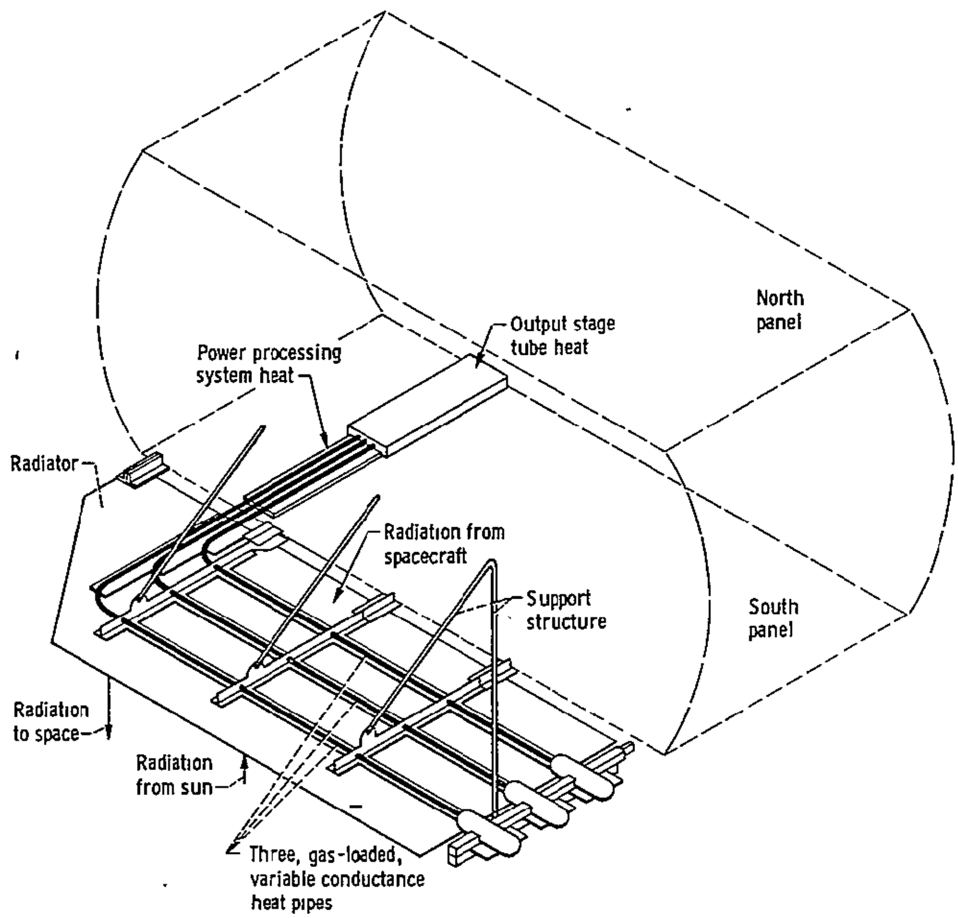


Figure 6-8. Variable Conductance Heat Pipe System (Variable conductance feature thermally disconnects transmitter experiment package during TEP power-down condition.)

The radiator on the first engineering model VCHPS (SN001) was coated with Kapton and Kapton film heaters instead of the silvered Teflon tape. The heaters were required to simulate insolation during thermal vacuum testing in the absence of solar simulation and Kapton was substituted for the more costly silvered Telon since specular characteristics of the radiator coating were not required for the tests planned with SN001.

A small radiator is provided for each of the reservoirs (Figure 6-21). These radiators which are coated with silvered Teflon maintain the proper temperature range on the reservoir necessary for the control aspects of the heat pipes.

The radiator support structure (tees and stiffening flange) shown in Figure 6-8 provide the stiffness necessary to minimize the magnitude of radiator deflections under the vibration environments shown in Table 6-3. Since the radiator is cantilevered from the spacecraft's South Panel (Figure 6-1), the tees provide the point of attachment for three of the five spacecraft attachment fittings (Figure 6-8) and the support struts (Figure 6-1). Thus, the tees transmit the loads associated with the radiator mass back to the spacecraft.

The heat pipe reservoirs are supported by the reservoir support assembly (Figure 6-8). This assembly is a rectangular, fiberglass box beam which attaches to the spacecraft's South Panel at one of the spacecraft's fittings designated for VCHPS use.

The five spacecraft attachment fittings which provide the load transfer path for radiator loads are fiberglas to minimize the heat transfer from the spacecraft to the VCHPS radiator. Fittings numbered 1, 2, 2 1/2 and 4 in Figure 6-9 incorporates a slip capability along the X-axis to accommodate the differential thermal expansion between the radiator and spacecraft's South Panel during orbital conditions where the radiator is significantly colder than the South Panel.

The struts shown shcmeatically in Figure 6-9 are fiberglass tubes wrapped with a multilayer, aluminized maylar wrap (Figure 6-25). The tubes stabilize the outboard section of the radiator during Y-axis loading. The aluminized mylar wraps and fiberglass material of the struts minimize conduction heat loss from the spacecraft.

6.4 DESIGN ANALYSIS

This section of the report presents the summary of the design analyses conducted in support of the VCHPS design prior to fabrication and a discussion of the design verification analyses subsequent to heat pipe testing. The reader is referred to the preliminary design review data package (Reference 4) for details of analyses conducted in support of the VCHPS design.

6.4.1 VCHPS Thermal Performance

The thermal performance characteristics of the VCHPS are summarized in Figures 6-10 and 6-11. The performance of the VCHPS is predicted utilizing an integrated thermal model of the VCHPS, TEP baseplate, CTS South Panel and MDC/OST. The thermal model is programmed for use on the SINDA computer program. For the details of the thermal model the reader should refer to Reference 5.

Figure 6-10 shows the VCHPS characteristic (evaporator saddle temperature versus system heat rejection) for the limiting design conditions: one heat pipe failed (outboard heat pipe) at maximum and minimum sink conditions. The radiator heat rejection shown in Figures 6-10 and 6-11 is based on end-of-mission α_S/ε ratio for the silvered Teflon ($\alpha_S/\varepsilon = 0.25$). At the beginning of the mission $\alpha_S/\varepsilon = 0.11$ and the radiator will achieve the same heat rejection at a lower evaporator saddle temperature.

The VCHPS performance characteristic for the same design conditions as in Figure 6-10 but with all heat pipes operating is shown in Figure 6-11. Comparing the two system characteristics (Figures 6-10 and 6-11) shows that with all heat pipes operating the design heat rejection (196 watts) is achieved at an evaporator saddle temperature from 1 to 4°C cooler than for the one heat pipe failed condition.

The system capabilities under maximum design conditions of summer solstice environment, end-of-mission silvered Teflon α_S/ε and a 50°C (122°F) evaporator saddle temperature are shown in Table 6-7 for the possible combinations of two heat pipes operating. The performance margin shown represents the margin for accomodating either load increase or degradation in radiator performance.

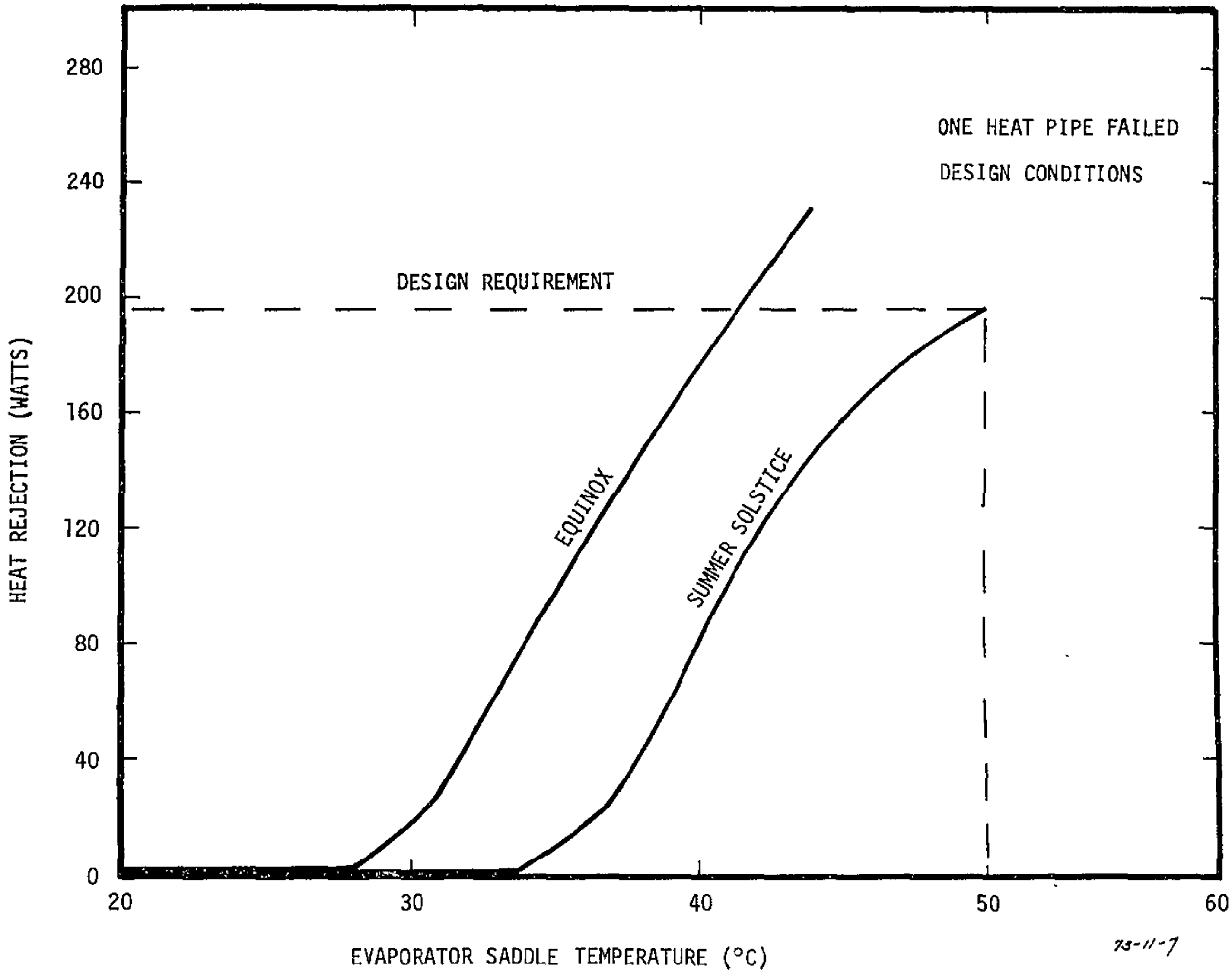


Figure 6-10. VCHP System Performance

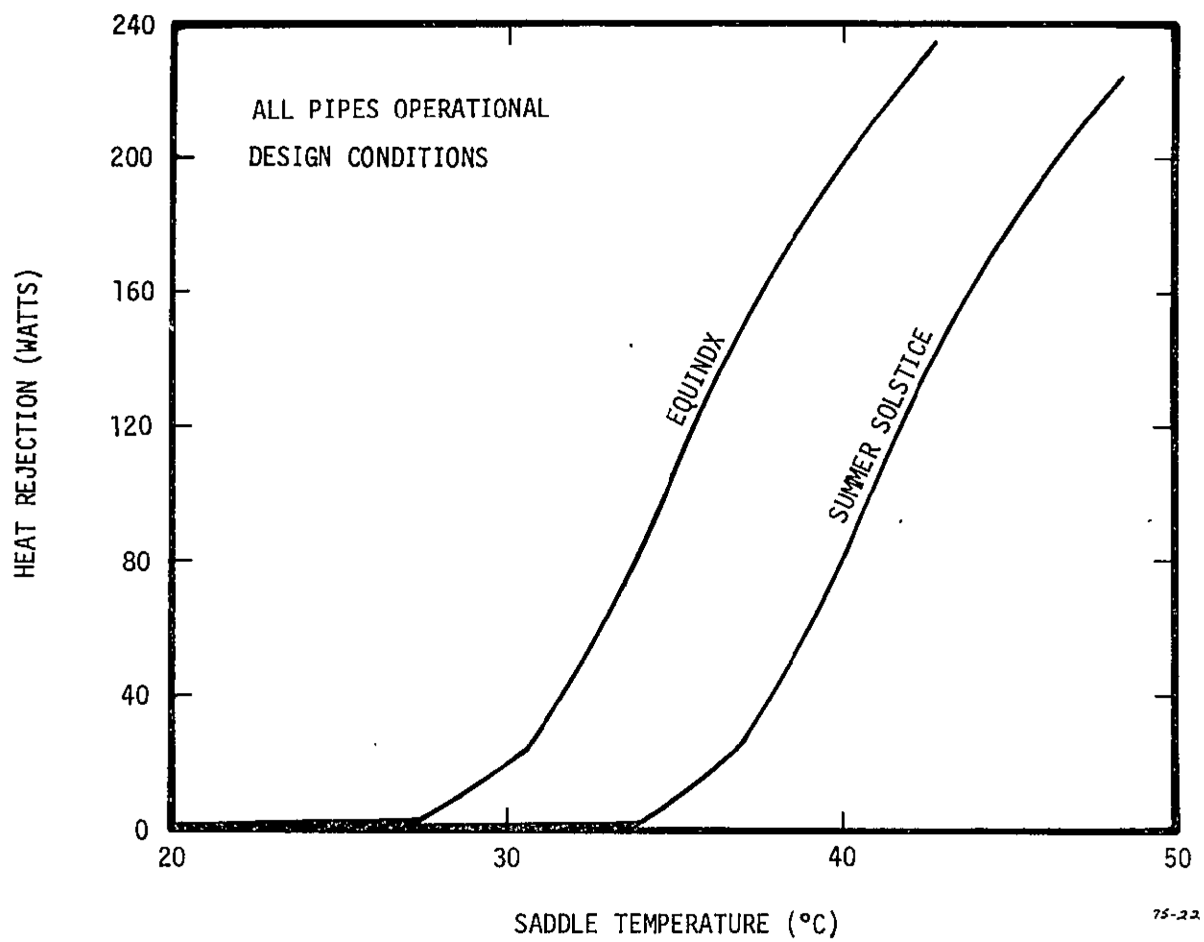


Figure 6-11. VCHP System Performance

Table 6-7. TEP Variable Conductance Heat Pipe System Performance
Summer Solstice

CONDITIONS	SYSTEM PERFORMANCE*	
	LOAD (WATTS)	MARGIN (%)**
1. Design Case (#3 Failed)	196	25
2. Middle (#2) Pipe Failed	208	33
3. Inboard (#1) Pipe Failed	198	27
4. All Pipes Operating	240	54

*At a 50°C Saddle

**Margin based on 156 watt load

6.4.2 Heat Pipe Performance

The individual heat pipe zero-gee performance predictions for the SN004 and SN005 VCHPS are presented in Table 6-8. These predictions are based on heat pipe performance data from performance testing in a one-gee environment. For the pretest heat pipe performance predictions, the reader should consult Reference 4. The heat pipe zero-gee capacity predictions were made using the TRW MULTIWICK computer program (Reference 6). The model of the TEP heat pipes was adjusted for artery diameter and priming foil pore size. The pore size that matched the average of the artery bubble point data was established (0.0105 inches) and then used in MULTIWICK to determine the artery diameter that exactly predicted the RSS capacity from all one-gee test data on the -1 heat pipe. The basing of the artery diameter on test data results from the belief that previous predictions (Reference 4) used an artery diameter that was too small. Previous predictions used a 0.063 inch artery diameter which is the diameter of the mandrel used to form the artery. Since the effective artery diameter must be greater than the mandrel and the heat pipe capacity varies as the fourth power of the diameter, a small increase in this parameter can significantly increase the predicted capacity. The artery diameter necessary to match test data is 0.0637 inches, an increase of only 1 percent.

As shown in Table 6-8, the predicted zero-gee heat pipe capacity on the number two (-2) heat pipe of the SN004 VCHPS is less than for the same pipe on the SN005 VCHPS. The lower performance results from an anomolous performance of the noted pipe during one-gee testing (Reference Section 5.2). In order to assess the cause of the anomolous performance of the number two heat pipe on SN004, an analysis was conducted of the test results.

The adjusted MULTIWICK model was used to determine the flaw size necessary to match the performance of the out-of-spec heat pipe on the SN004 VCHPS (-2 heat pipe). The variation of maximum heat transfer rate in the pipe with flaw size is shown in Figure 6-12. Using the average between the heat transfer rate the heat pipe held and that at which it failed in one-gee testing, the predicted flaw size is 0.0129 inches.

Table 6-8. TEP Heat Pipe Margins

196 WATT CASE HEAT PIPE	T_{SADDLE}	'0g' LOAD	'0g' CAPACITY*	MARGIN (%)
#1				
#2 failed	121	93	178	91
#3 failed	122	80	178	122
#2				
#1 failed	122	108	167 (136)	57 (28)
#3 failed	122	116	167 (138)	44 (18)
#3				
#1 failed	122	90	174	93
#2 failed	121	104	172	65
156 WATT CASE				
#1				
#2 failed	112	80	176	120
#3 failed	113	76	174	129
#2				
#1 failed	116	97	178 (143)	84 (47)
#3 failed	113	79	192 (155)	143 (96)
#3				
#1 failed	116	59	197	233
#2 failed	112	76	201	165

*For heat pipe No. 2, Nos. in () refer to SN004; All other entries refer to both SN004 and SN005.

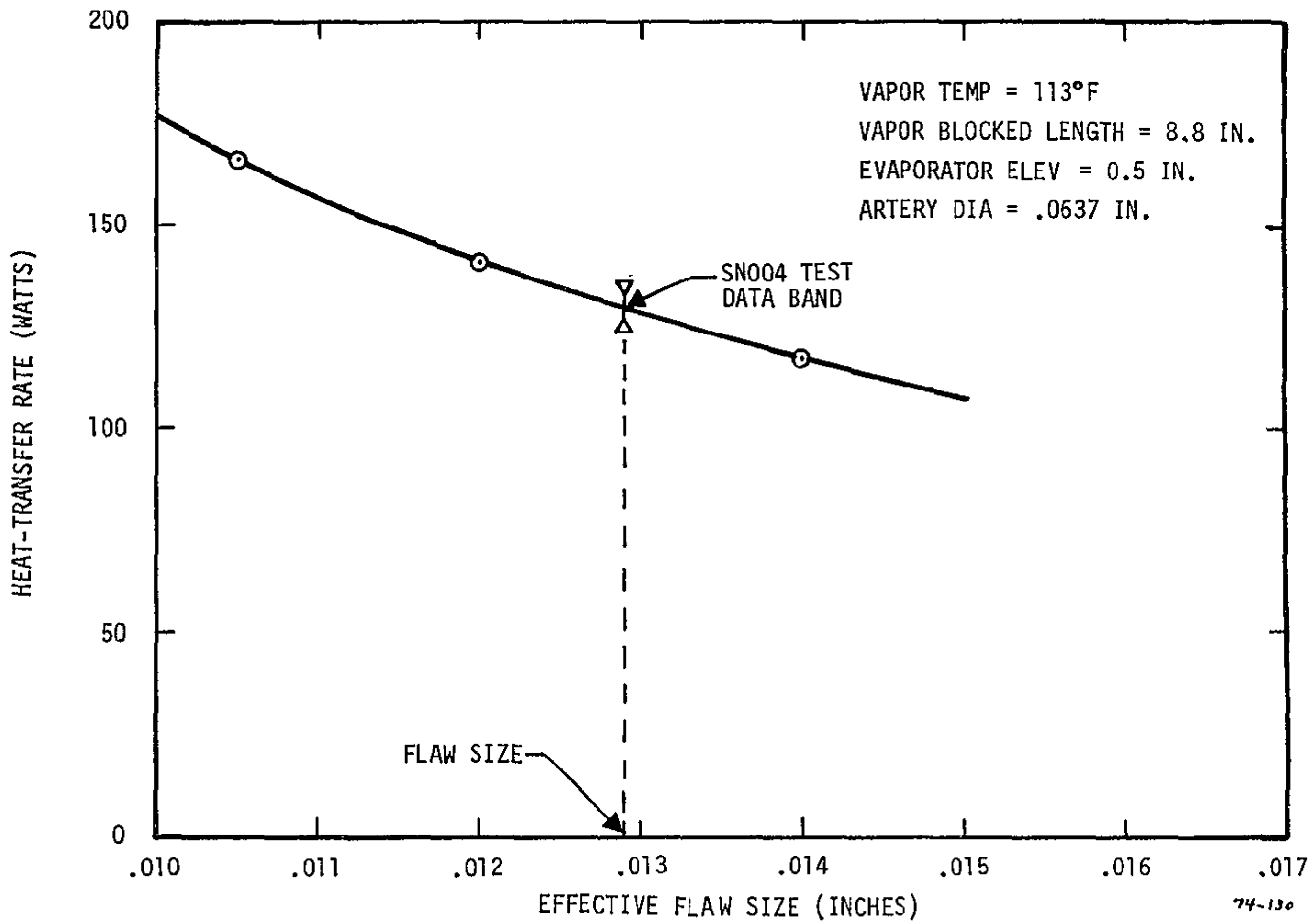


Figure 6-12. SN004 No. 2 Heat Pipe

This heat pipe model was then used to predict the heat pipe capacities for the SN004 VCHPS for the heat pipe operating conditions predicted from the SINDA thermal model of the TEP heat pipe installation (Reference 5). The operating temperatures and heat transfer rate (load) requirements for various operating heat pipe combinations under radiator heat rejection levels of 156 watts and 196 watts (specification load) were obtained.

Table 6-8 presents the heat pipe margins for all combinations of two heat pipes operating for radiator heat rejections of 156 and 196 watts. Because of the damaged artery on the -2 pipe for the SN004 VCHPS, the minimum margin occurs on this pipe. While the pipe has only an 18 percent margin for the specification loads, it does have adequate margin for the predicted loads at the predicted system heat rejection of 156 watts.

Heat pipe capacities on the -3 heat pipe generally tend to be higher than the -2 pipe because the percentage of the condenser that is vapor blocked is greater. The capacities presented are based on the effective lengths for thermal energy transport that result from the SINDA thermal models predictions of degree of heat pipe turn-on (vapor blocked lengths).

6.4.3 Structural Performance

This section presents the structural and dynamic loads analyses conducted to verify the VCHPS was structurally adequate for all the imposed loading conditions. The VCHPS was modeled both statically and dynamically for analysis with the TRW Static Structural Analysis Program (SSAP) and the Structural Model Analysis Program (SMAP) respectively. For a discussion of the model and analysis boundary conditions the reader is referred to Reference 4.

6.4.3.1 Stress Analysis

The SSAP was used to predict the interface reaction loads shown in Table 6-9. As shown, the slip feature of the spacecraft/radiator interface fittings at the South Panel (Joints 1, 2, 2 1/2 and 4, Figure 6-9) requires that the 75 gee loading along the X-axis be reacted totally by Joint 3 and the heat pipes bridging the radiator/South Panel interface plane. Accordingly, the interface attachment fitting was designed to react the total load in shear along the X-axis.

Table 6-9. Interface Reaction Loads
(Reference to S/C Coordinate System, Figure 6-9)

Interface Location	Loading Condition	FX (LB)	FY (LB)	FZ (LB)	MX (IN-LB)	MY (IN-LB)	MZ (IN-LB)
JT.1		-2	0	-39	0	-2	1
JT.2		-2	0	-140	0	-2	0
JT.2 1/2		-2	0	-220	-1	-2	0
JT.3	n_x=+75gs	-1082	0	-83	0	-1413	0
PIPES	(East)	-67	0	236	0	-173	0
JT.4		-2	0	246	0	-2	0
JT.5		-3	-2	-2	-1	-2	1
JT.5 1/2		0	1	2	-1	-2	1
JT.6		0	0	0	0	-2	1
JT.1		0	-51	107	114	0	-12
JT.2		0	-78	352	228	0	2
JT.2 1/2		0	-71	276	193	0	0
JT.3		-103	-74	204	208	-130	3
PIPES	n_y=+75gs	-6	-56	113	278	-15	-51
JT.4	(South)	0	-40	29	210	0	12
JT.5		109	-340	-474	8	5	-6
JT.5 1/2		0	-215	-288	1	3	-2
JT.6		0	-237	-318	0	-1	-1
JT.1		0	1	-125	-2	0	0
JT.2		0	0	-360	0	0	0
JT.2 1/2		0	0	-284	0	0	0
JT.3		-1	0	-229	0	-5	0
PIPES	n_z=+75gs	0	0	-126	-1	0	0
JT.4	(Forward)	0	0	-39	0	0	0
JT.5		1	-1	-1	0	0	0
JT.5 1/2		0	0	0	0	0	0
JT.6		0	0	0	0	0	0
JT.1		0	-1	620	2	0	7
JT.2		0	-1	-708	29	0	0
JT.2 1/2		0	-1	-193	26	0	0
JT.3	Cold Soak	-35	-3	-851	43	-97	0
PIPES		45	-1	1134	26	113	1
JT.4		0	0	-13	1	0	0
JT.5		-10	-6	-7	-3	-6	3
JT.5 1/2		0	10	13	-1	-2	2
JT.6		0	4	5	0	1	0

The moments shown in Table 6-9 for all fitting joints were transmitted to the Spacecraft contractor for evaluation of effects on the Spacecraft side of the interface. To date, there has been no indication that either the loads or moments are excessive.

The minimum margins of safety resulting from the loading conditions shown in Table 6-9 are presented in Table 6-10. As shown, the minimum margin occurs on the -3 heat pipe during the eclipse portion of the mission where the radiator is at the minimum temperature and the South Panel is near ambient conditions.

The 304 stainless steel heat pipe/6061 aluminum saddle combination presents a unique stress problem due to the thermal cycling that occurs during orbital operation. When the heat pipes shut off, the radiator cools down and approaches the effective space sink temperature of -93°C (-135°F) for equinox conditions or -65°C (-85°F) for summer solstice conditions. Thus, the gas blocked portion of the heat pipes on the radiator also approach the effective sink conditions. The mismatch in coefficients of thermal expansion for the stainless steel and the aluminum results in a shear stress in the heat pipe/saddle solder joint. In order to qualify this type of joint for thermal cycling fatigue strength, a test program was conducted (funded by another TRW heat pipe program) because of the difficulties associated with analytical treatment of the problem.

Samples of heat pipe/saddle joints were thermally cycled and periodically examined. The test temperature range and number of cycles at each temperature range are shown in Table 6-11. Following testing the test articles were examined and in some cases sectioned to examine the subsurface (body) postion of the solder joint. Other than surface crazing, which was expected, no degradation of the solder joints was noted.

6.4.3.2 Dynamics Analysis

The dynamics analysis utilized the SMAP which uses the same analytical mode and the same basic data as used in the SSAP (Reference 4). The structure is considered as small masses which are lumped at the joints of the structure. The solution is based on small deflection theory using the direct stiffners matrix, finite element approach using linear stiffnesses (Reference 4).

Table 6-10. Minimum Margins of Safety

LOADING CONDITION	CRITICAL MEMBER (1)	MEMBER DESCRIPTION	MEMBER MAT'L	MARGIN OF SAFETY
n_x = +75g's (East)	Member 64, Jt. 111	Heat Pipes @ South Panel Interface	304 St. St.	1.17 (yld.)(2)
n_y = +75g's (South)	Member 56	Tubular Strut	Fiberglass	0.18
n_z = +75g's (Forward)	Member 34, Jt. 34	Heat Pipe	304 ST. St.	Large
Cold Soak (3)	Member 26, Jt. 15	Heat Pipes at South Panel Interface	304 ST. ST.	0.11 (yld.)

Notes:

(1) Member numbers and joint numbers relate to analytical model. (Reference 9)

(2) Yield condition is critical where noted otherwise the ultimate load case is critical. Plastic bending effects are included in all cases where the heat pipe tubes are critical.

(3) Cold soak condition is based on maximum eclipse time with the radiator at the coldest operational condition at time of passing into eclipse.

Table 6-11. Heat Pipe/Saddle Solder Joint Thermal Cycling Test Environment

TEST TEMPERATURE RANGE (°F),(1),(2)	NUMBER OF CYCLES
+20 to +105	7700
-130 to +90	7700
-200 to 0	1300
-120 to 0	7500

(1) Test temperatures to be maintained within following limits:

- Minimum temperature: $^{+0}_{-10}$ °F
- Maximum temperature: $^{-0}_{+0}$ °F

(2) This value to be based on the average temperature of the thermocouples attached to the tube wall and to the saddle.

The resulting frequencies and modes are shown in Table 6-12. The first mode frequency occurs at 34.6 Hz as a "flapping" motion of a portion of the radiator along the most outboard edge. As shown, the first natural frequency is greater than 20 Hz and is within the design goal of 25 to 35 Hz.

6.4.4 Weights and Mass Properties

The VCHPS measured weights are shown in Table 6-13. The reduction in flight weights relative to measured weights results from the weight associated with the simulator tube AN fittings and the blue protective coverlay on the silvered Teflon.

The VCHPS nominal center of gravity and mass inertia values are shown in Table 6-14 and Figure 6-13. The center of gravity and inertia values were based on the weight measured for SN002 converted to an equivalent flight weight of 16.15 lbm.

6.5 VCHPS TESTING

This section of the report presents the results of the heat pipe system test program. The test program was conducted at both TRW and NASA/LeRC. Tests conducted at TRW were the heat pipe subassembly performance test and the VCHPS functional acceptance test. The SN001 VCHPS was tested for both structural capability (vibration test) and thermal performance coupling with the spacecraft's South Panel by NASA/LeRC. In addition, the SN004 VCHPS will be used for spacecraft thermal vacuum testing by the Canadian Communications Research Center (CRC). This latter test was scheduled to commence during the writing of this report.

6.5.1 Heat Pipe Priming Test

The heat pipes are required to be able to self-prime at conditions which range from ambient temperature down to near the freezing point of methanol. Accordingly, the initial methanol inventory was established to achieve this capability. However, the inventory required for priming is somewhat difficult to predict for the complex wick structure used in the VCHPS which necessiated conducting priming tests to verify arterial priming capability.

Table 6-12. Frequencies and Modes

MODE	FN (Hz)	LOCATION
1	34.6	Center, Top Edge, Panel
2	35.0	Corner, Top, Panel
3	40.5	Corner, Bottom, Panel
4	44.9	Corner, Top, Panel
5	46.5	Center, Top Edge, Panel
6	54.5	Corner, Top, Panel
7	55.1	CTR, Bottom Edge, Panel
8	57.6	CTR, Bottom Edge, Panel
9	59.3	CTR, Bottom Edge, Panel
10	62.8	Center, Top Edge, Panel
11	63.9	CTR, Bottom Edge, Panel
12	77.4	Center, Top Edge, Panel
13	85.0	CTR, Bottom Edge, Panel
14	95.5	Top, Column 3
15	105.8	CTR, Side, Stiff Edge, Panel
16	117.8	Corner, Top, Panel
17	120.9	Middle, Panel
18	127.5	CTR, Side, Edge, Panel
19	130.4	CTR, Interior Panel
20	135.0	CTR, Interior Panel

Table 6-13. VCHPS Weights[1]

UNIT SERIAL NO.	MEASURED WEIGHT (lbm)	FLIGHT WEIGHT (lbm)
001	16.09	N/A
002	16.43	N/A
004	16.58	16.30
005	16.68	16.40

Note:

1. Weight accuracy is ± 0.05 lbm.

Table 6-14. Heat Pipe Assembly Mass Properties

MASS PROPERTY PERAMETER		HEAT PIPE SYSTEM ON S/C SOUTH PANEL	HEAT PIPE SYSTEM OFF S/C SOUTH PANEL
CENTER OF GRAVITY**	($\bar{X}$ = IN)	15.00	-3.70
CENTER OF GRAVITY**	($\bar{Y}$ = IN)	26.16	25.83
CENTER OF GRAVITY**	($\bar{Z}$ = IN)	30.78	55.86
INERTIA	(I_{xx} + LB-IN^2)	185	361
INERTIA	(I_{yy} = LB-IN^2)	188	2941
INERTIA	(I_{zz} = LB-IN^2)	4	2618

**Center of gravity locations are referenced to the spacecraft coordinate system shown in TRW Drawing 315257.

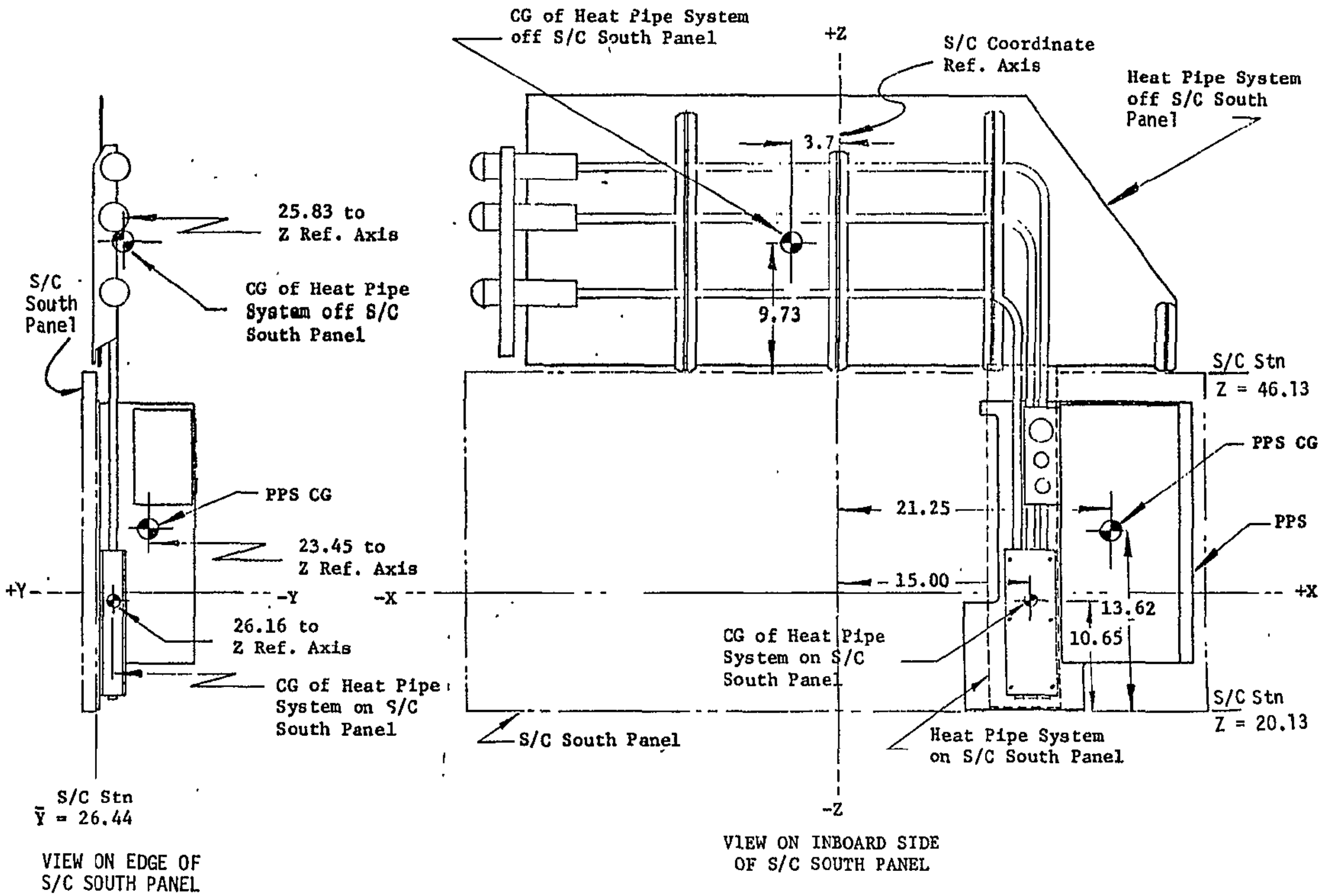


Figure 6-13. Center of Gravity Locations of Power Processor and Heat Pipe Assembly

The priming test was conducted by installing the SN001 heat pipe subassembly on a tiltable cold plate. The cold plate temperature was varied over a range of -7°C (20°F) to -90°C (-130°F) for the priming test.

After establishing the sink (cold plate) temperature conditions, the heat pipe subassembly was leveled to allow the arteries to prime. The reservoirs of the two heat pipes not under test were heated to expand the control gas and gas block the condensers so as to effectively shut off the heat pipes. This operation was required because all three heat pipes share a common evaporator saddle. Thus, to ensure that all the energy from the evaporator heater goes into the heat pipe being tested, the other two pipes must be shut off.

The heat pipes were elevated with the evaporator higher than the condenser and up to 175 watts of power was applied to the heater. The -3 heat pipe was tested at three sink conditions (-7°C, -57°C and -90°C). Methanol was added until priming was achieved at each sink condition as verified by the heat pipe operating with the 175 watts of heater power. To achieve priming over the total temperature range 25cc of methanol were added to the -3 pipe.

Based on the test of the -3 pipe, the liquid inventories of the -1 and -2 pipes were increased by 25cc. Both pipes were then tested over the total temperature range to verify that the liquid inventories were sufficient for priming. The final design liquid inventories for each of the three pipes is shown in Table 6-15.

6.5.2 Heat Pipe Performance Test

The individual heat pipe performance tests were conducted to verify control gas inventory and integrity of the internal wick structure. The tests were conducted at the heat pipe subassembly level. The performance testing was conducted by procedure MC-13C-01B.

Table 6-15. Heat Pipe Methanol Inventories

HEAT PIPE	NOMINAL INVENTORY (cc)
-1	89
-2	94
-3	98

6.5.2.1 Heat Pipe Control Range Test

The control range test is conducted to verify that the desired control gas inventories (Table 6-16) were loaded during the heat pipe fill process. The verficiation of control gas inventory is accomplished by testing the heat pipes at predetermined condenser and reservoir sink conditions which will produce a known heat pipe turn-on temperature. The actual heat pipe turn-on temperature under the test conditions determines whether or not the proper gas inventory was loaded. However, this turn-on temperature is not the turn-on temperature associated with the minimum sink conditions during the mission.

In addition, the gas inventories of the three heat pipes were established so as to stagger the heat pipe turn-on temperature such that the pipes turn-on in sequence. This feature of the heat pipes is also verified during the control range test.

Table 6-16. Heat Pipe Control Gas Inventory

HEAT PIPE	NOMINAL INVENTORY (10^{-6} lb-moles)
-1	3.94
-2	4.83
-3	5.76

The turn-on temperatures exhibited during the test are shown in Table 6-17. The variation in turn-on temperatures for a specific pipe from assembly to assembly (except SN006) results from the tolerances on gas fill as well as the tolerances in establishing cold plate and reservoir temperatures. The low turn-on temperatures for SN006 are suspected to have resulted from a malfunctioning pressure transducer during the gas fill operation. The SN006 gas inventory out-of-spec

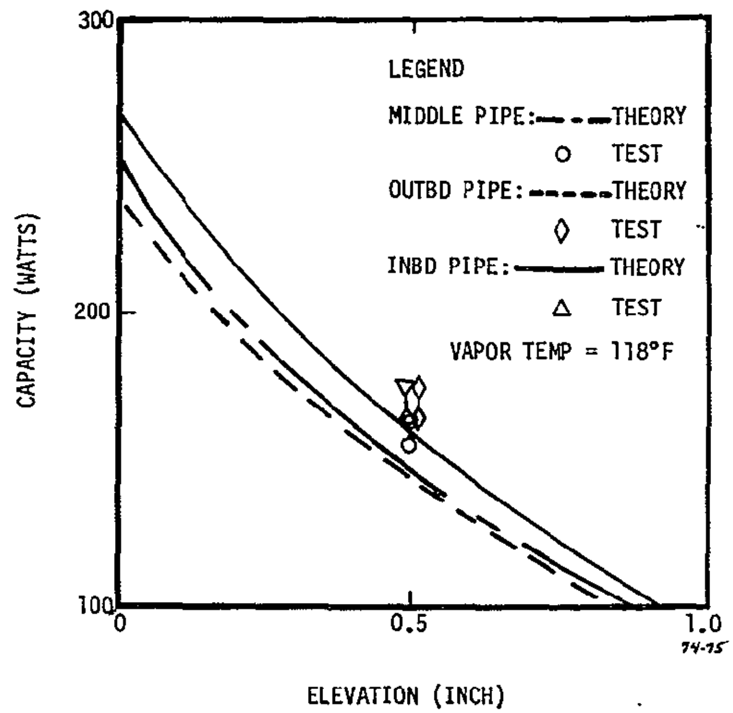


Figure 6-14. SN001 Assembly Performance Test Results

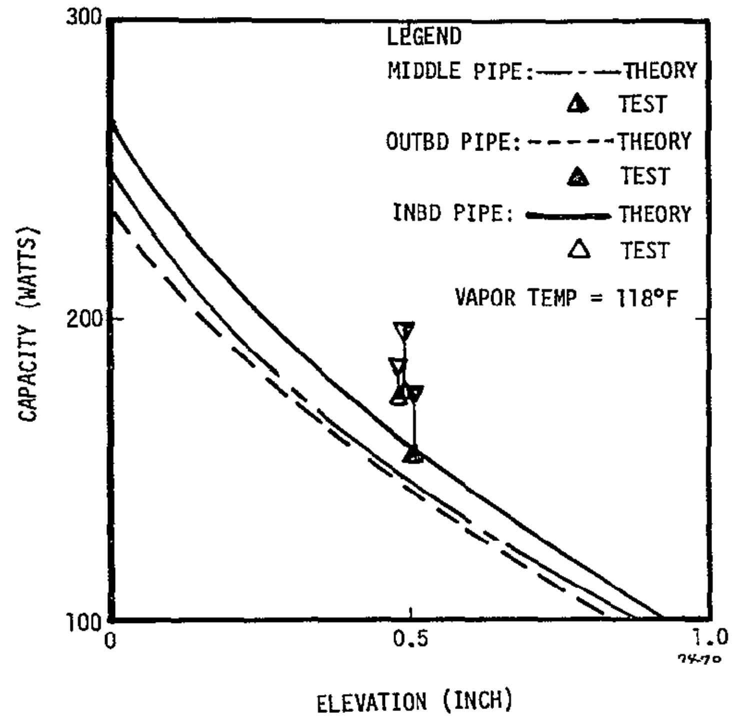


Figure 6-15. SN002 Assembly Performance Test Results

condition was accepted since this unit is for heat pipe life testing where turn-on conditions are not particularly important. Also shown in Table 6-17 are the magnitude of the turn-on temperature staggering for each unit.

6.5.2.2 Heat Pipe Capacity Test

The heat pipe capacity test was conducted to verify the integrity of the internal wick structure. The capacity tests define the maximum capacity of the heat pipe is a one-gee field. This capacity, when compared with the predicted capacity, provides insight into the soundness of the wick structure: a low test capacity is an indication that the wick structure may not be sound.

The capacity tests are conducted with the heat pipes mounted on the test fixture, insulated and elevated such that the evaporator is one-half inch above the condenser. Since the heat pipes are tested at the subassmbly level and elevated as a unit, the one-half inch is established on the -2 heat pipe. Thus, the -1 heat pipe is elevated slightly less and the -3 heat pipe slightly more than one-half inch.

The individual heat pipe capacities as determined by testing are compared with theoretical predictions in Figures 6-14 through 6-18 for SN001 through SN006, respectively. The tests are conducted by increasing the applied power in increments and allowing the heat pipe to equilibrate after each power increment. Thus, the test data are presented in the figures as the last power level at which the heat pipe successfully equilibrated and the power level at which it failed. The actual one-gee capacity of the heat pipe falls somewhere within the data band shown in the figures.

The number 2 heat pipe on the SN004 and SN006 assemblies did not meet the predicted capacities (Figures 6-16 and 6-18). As discussed previously (Section 4.2), the lower performance on the -2 heat pipe on SN004 is most likely due to a larger than normal opening in either the artery or priming foil. By comparison, it would appear that the same situation exists for the -2 heat pipe on the SN006 assembly since it appears to have performed similar to the SN004 heat pipe.

Table 6-17. Control Range Test Results

HEAT PIPE	SPEC TURN-ON TEMPERATURE RANGE (°F)	TEST TURN-ON TEMPERATURE (°F)				
		S/N001	S/N002	S/N004	S/N005	S/N006
D315260-1	88 ± 4	89	90	87	86	83*
D315260-2	94 ± 4	93	92	91	90	89*
D315260-3	100 ± 4	97	99	97	96	95*

*Out-of-spec temperatures acceptable since S/N006 is life test unit only.

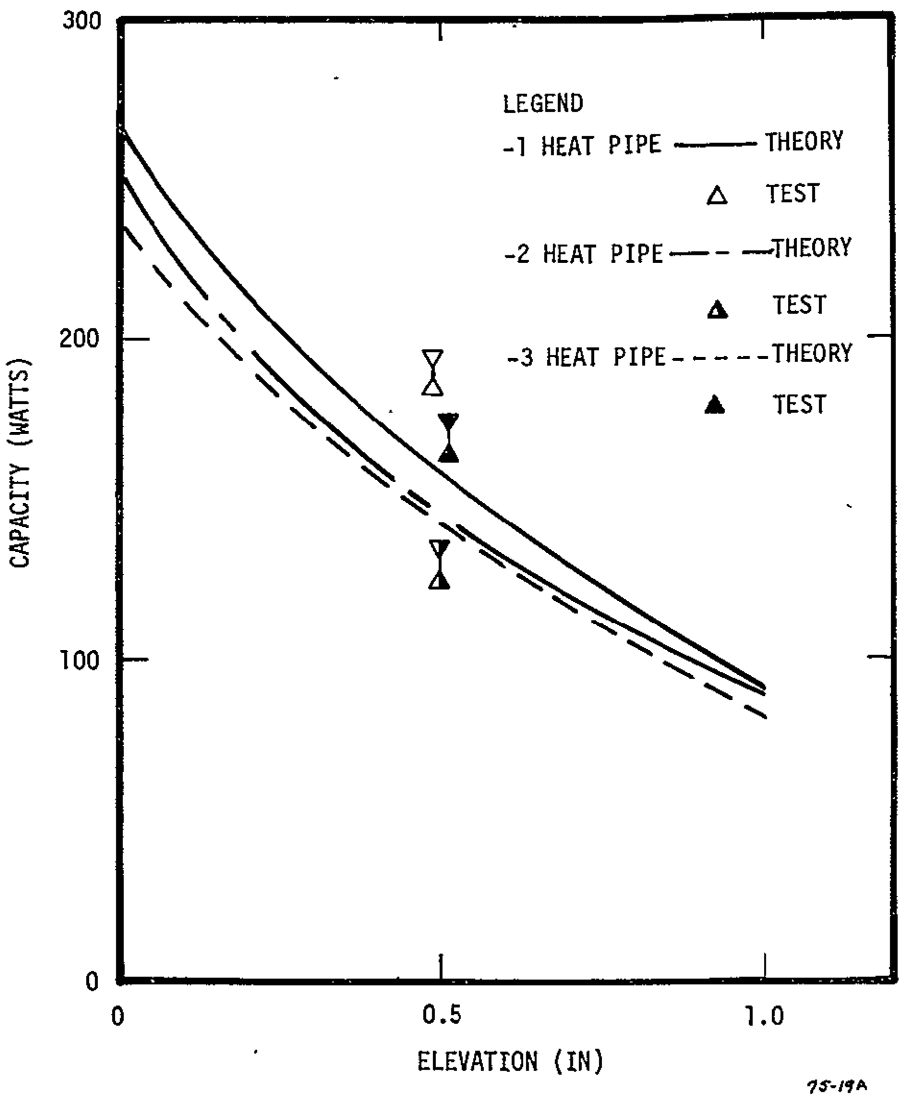


Figure 6-16. SN004 Assembly Performance Test Results

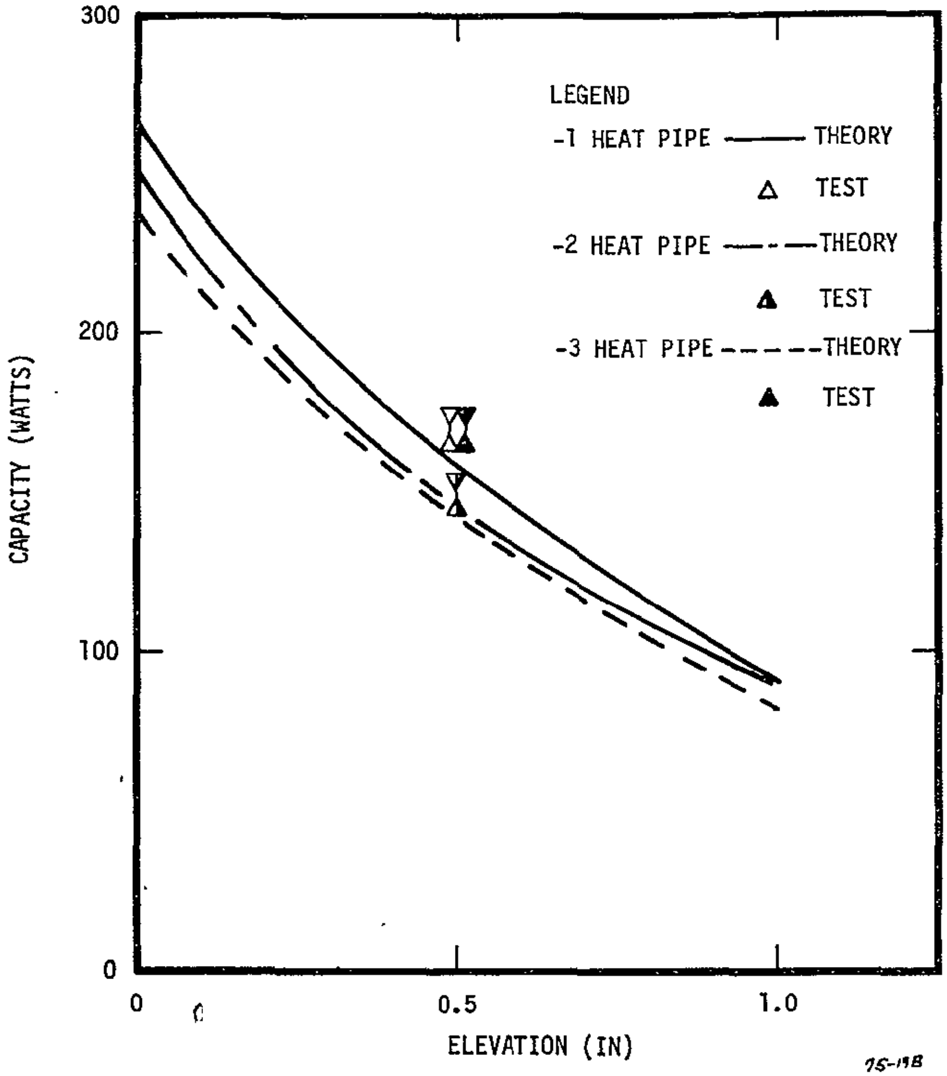


Figure 6-17. SN005 Assembly Performance Test Results

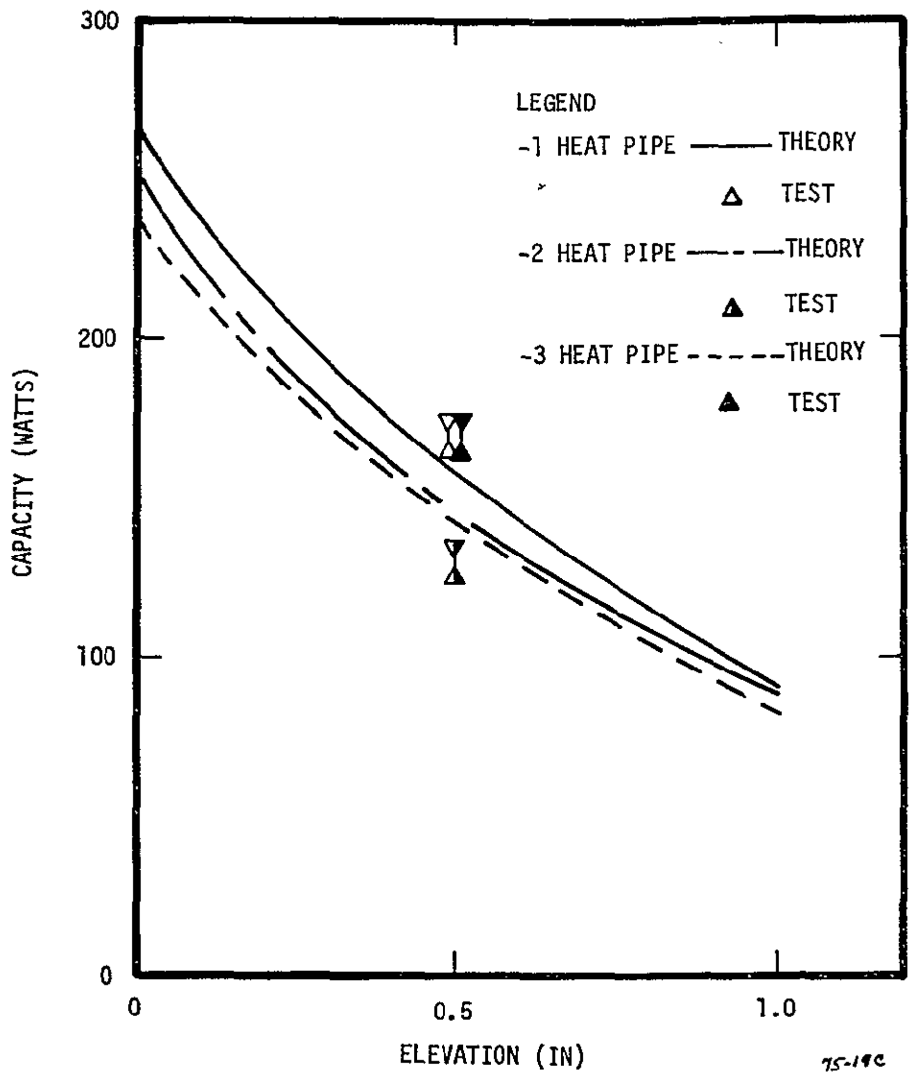


Figure 6-18. SN006 Assembly Performance Test Results

6.5.3 Functional Acceptance Test

The functional acceptance test is performed at the VCHPS final assembly level to verify the integrity of the final closure of the heat pipes. Final heat pipe closure occurs after the heat pipe performance test and there is some risk of having a leaking pipe. The functional acceptance test is essentially three tests run sequentially: heat pipe turn-on, radiator ambient performance characteristic definition and system flux mode characteristic definition. The testing is performed per test procedure MC-13A-01 (Reference 2)

6.5.3.1 Heat Pipe Turn-On Test

The heat pipe turn-on test is conducted to qualify the heat pipe gas inventory. Since the heat pipe internal pressure is subatmospheric, leakage which may occur through the fill valve between performance testing and final closure will be into the heat pipe. In addition, gas generation during final closre would also be retained in the pipe. The effect of the leakage or gas generation is to raise the heat pipe turn-on temperature. Thus, an abnormally high turn-on temperature during this test is an indication of an excessive amount of control gas which could only come from leakage and/or gas generation.

The results of the turn-on tests are shown in Table 6-18 for all five VCHPS assemblies. Since SN006 does not have a radiator, a temporary radiator was installed for this test. The turn-on temperatures show no evidence of heat pipe leakage. The variation in temperature for a given pipe is primarily due to the tolerances associated with the gas fill operation when the heat pipes are processed for control gas.

6.5.3.2 Radiator Ambient Performance

The ambient radiator performance test is conducted to define the VCHPS performance characteristic in a one-atmosphere, ambient environment for use in control of tests conducted at the spacecraft assembly level. The test is run with the VCHPS oriented as shown in Figure 6-19. The evaporator is elevated one-half inch relative to the condenser to eliminate gravity aided puddle flow in the heat pipes. The performance characteristics for the two

Table 6-18. VCHPS Functional Acceptance Test Turn-On Temperatures

HEAT PIPE	TURN-ON TEMPERATURE SPECIFICATION (°F)	TURN-ON TEMPERATURES (°F)				
		SN001	SN002	SN004	SN005	SN006
D315260-1	110°F T 120°F	115	115	112*	113	112
D315260-2	112°F T 122°F	116	116	112*	114	114
D315260-3	114°F T 124°F	117	120	115	118	117

*The -1 heat pipe turned on immediately prior to the -2 heat pipe turn-on.

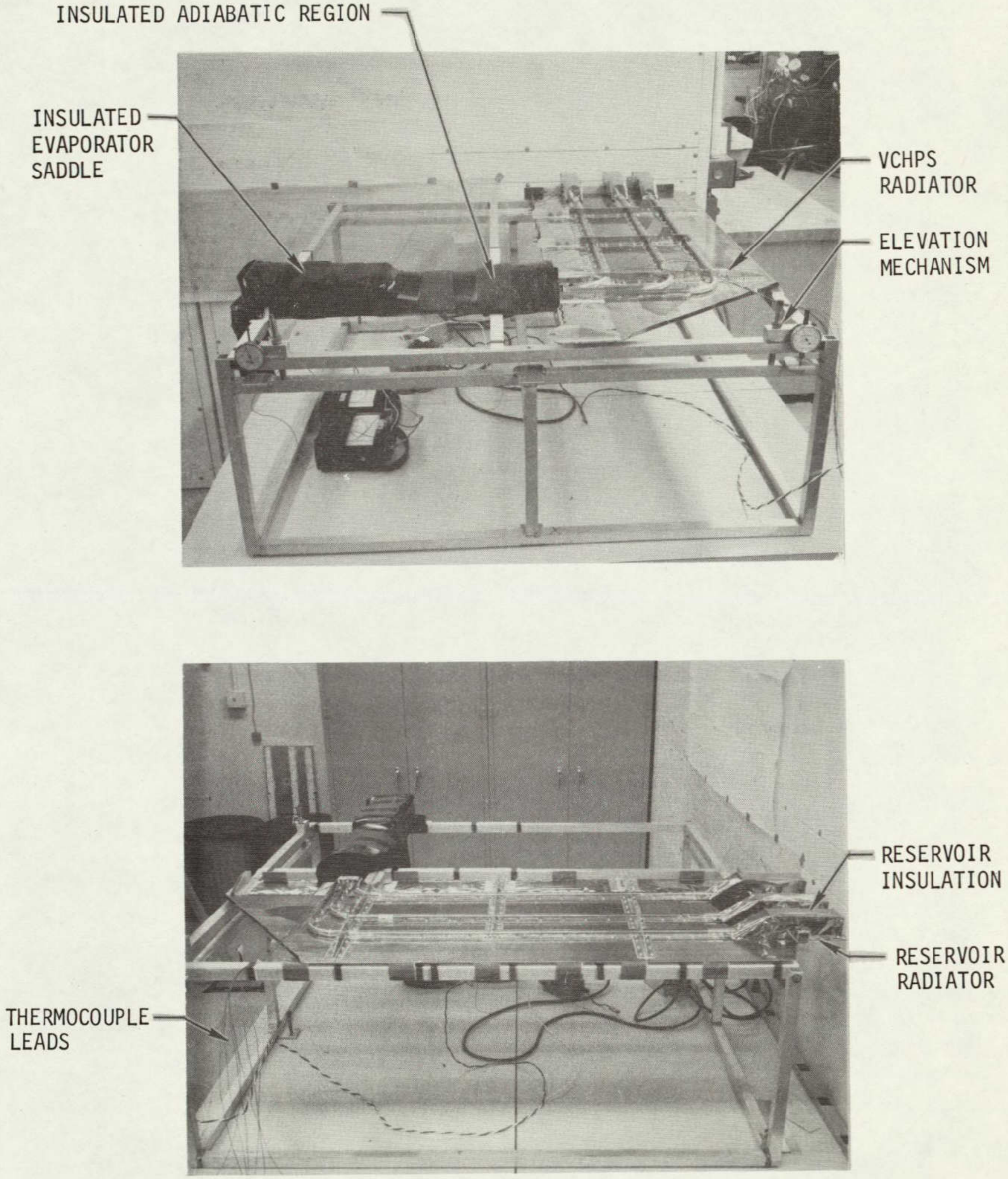


Figure 6-19. VCHPS Functional Acceptance Test Setup

flight assemblies (SN004 and SN005) are shown in Figure 6-20). As shown, both of the systems reached full on conditions; evaporator saddle temperature of approximately 53°C (128°F) for SN004 and 56°C (132°F) for SN005. At higher power levels the system is radiator heat rejection limited as shown by the highly nonlinear behavior of the systems beyond the noted evaporator saddle temperatures.

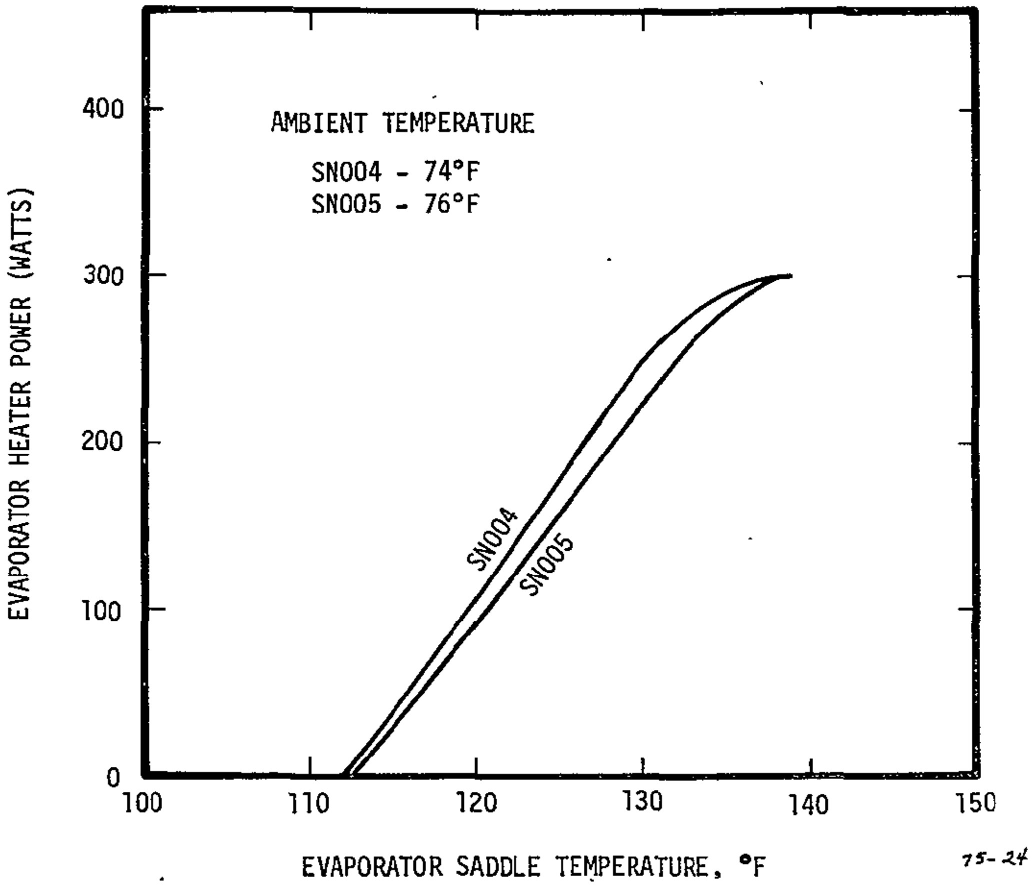


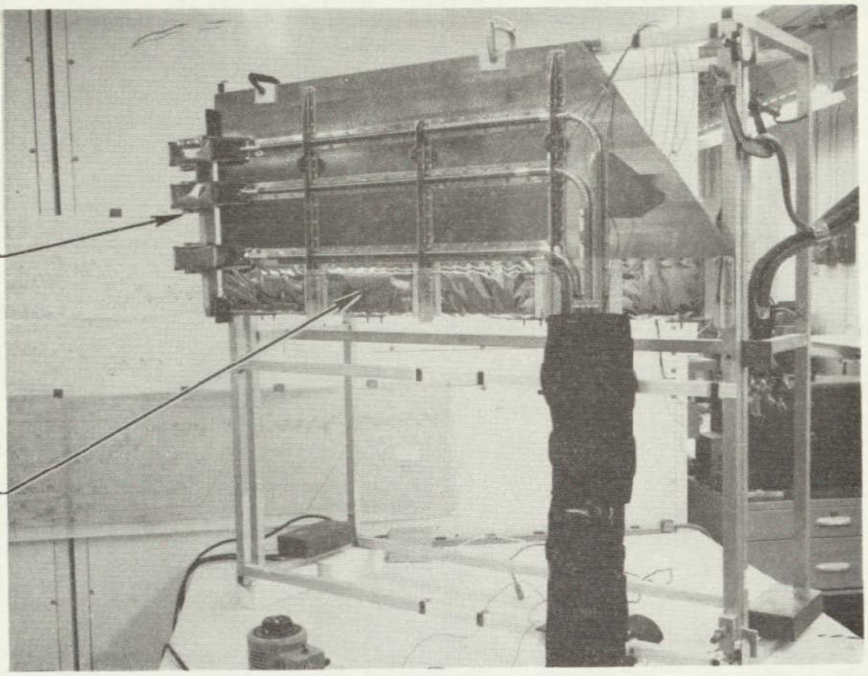
Figure 6-20. Functional Acceptance Test — Ambient Performance Characteristic

6.5.3.3 VCHPS Reflux Mode Tests

The VCHPS is tested in the reflux mode to define the system characteristic for testing when the VCHPS is integrated with the spacecraft and is in the reflux mode orientation. The reflux mode test setup is shown in Figure 6-21. In this test the radiator is elevated above the evaporator saddle and the fluid return from the condenser to the evaporator is gravity aided.

The reflux mode characteristic for SN004 is shown in Figure 6-22. A comparison of the test data on SN005 witn SN004 indicates that the methanol was apparently trapped in the SN005 reservoir during the setup for the test. This conclusion is based on the performance of SN004 as exhibited in Figure 6-22 which was obtained after tilting the reservoirs to ensure that they were not entrapping fluid. However, it is believed that SN005 when tested properly would exhibit a similar reflux mode characteristic as do SN002 and SN006.

The reflux mode response of SN004 exhibits three regions of operation. Initially, at the low power level, the excess fluid resides in the evaporator and heat transfer is through pool boiling of the fluid. Pool boiling requires a relatively large temperature differential between the evaporator saddle and the saturated vapor temperature (see Figure 6-23) because of the low thermal conductivity of the methanol. As the heater power increases, the methanol pool level is lowered which uncovers the grooves in the evaporator and allows the heat transfer to occur at a lower evaporator saddle temperature. As the heater power approaches 200 watts the combined hydrostatic and hydrodynamic stress on the grooves begin to initiate groove dryout. As the area of groove dryout increases, the wetted/dry groove interface recedes past the location of the evaporator saddle thermocouple. The temperature of the saddle increases as the necessary conduction distance to the wetted groove/liquid pool region increases. As the power approaches 300 watts a stable, combined pool boiling/groove heat transfer is approached.



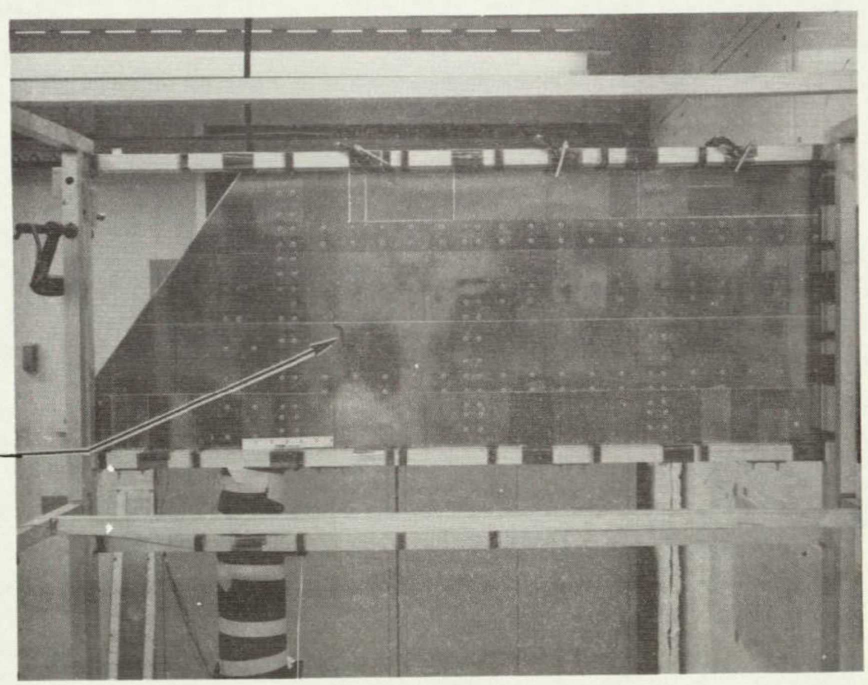


Figure 6-21. Functional Acceptance Test — Reflux Mode

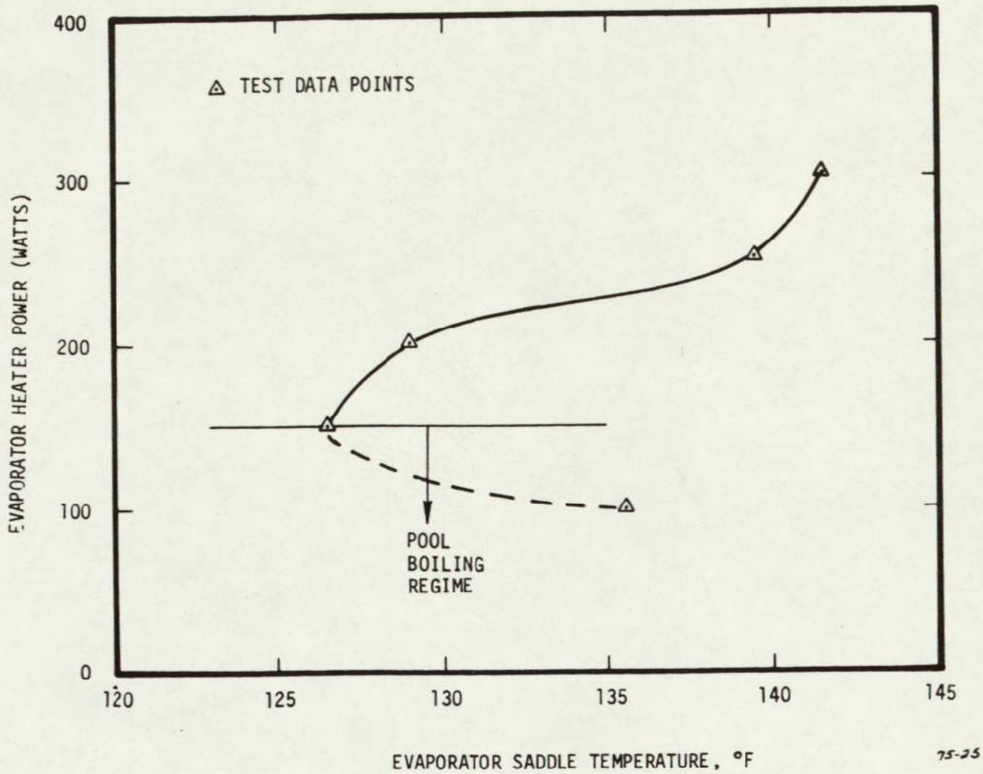


Figure 6-22. VCHPS Reflux Mode Characteristic — SN004

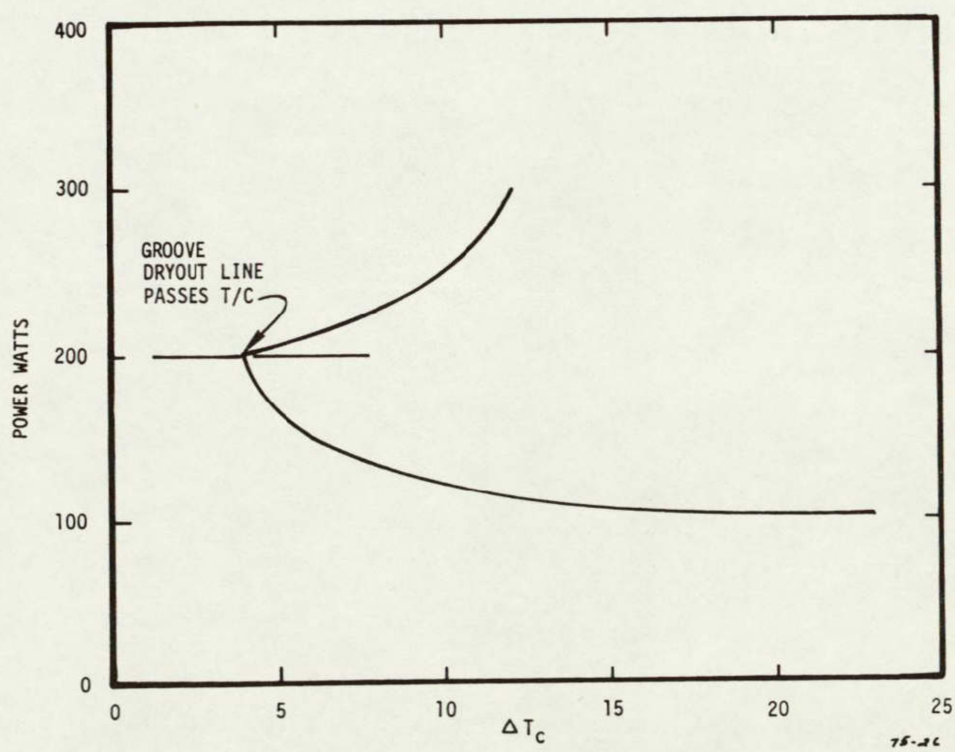


Figure 6-23. Evaporator Saddle to Vapor Temperature Difference — SN004 Assembly

Since the maximum expected load on the VCHPS is expected to be in the 150 to 160 watt range, the VCHPS would be expected to operate at an evaporator saddle temperature in the range of 52°C (125°F) to 54°C (130°F). This operational temperature can be lowered by increasing the radiator heat rejection with forced convection cooling or by the use of the heat pipe simulator tube and auxiliary cooling.

6.6 SOUTH PANEL THERMAL VACUUM TEST

The Spacecraft's South Panel thermal vacuum test was conducted with the SN001 VCHPS. The test was conducted jointly by NASA/LeRC and CRC personnel at NASA/LeRC. The test article is shown in Figure 6-24. As noted previously, heaters were bonded to the VCHPS radiator to simulate the insolation environment of the radiator.

The South Panel test was conducted to verify the performance of the VCHPS and South Panel as an integrated thermal control system. To accomplish the verification, both maximum and minimum sink condition tests were conducted.

6.6.1 Maximum Sink Tests

The maximum sink condition tests for the VCHPS are those associated with a summer midnight environment simulation on the VCHPS radiator (test cases 1, 2 and 7). Of the noted cases, case 7 was chosen for evaluation since it represents the maximum design conditions (i.e., maximum OST heat dissipation possible). A comparison of the case 7 test data with the TRW design analysis is presented in Figure 6-25. It is expected that the heat rejection capability of the test radiator would be greater than that of the analysis due to surface finish differences (Kapton emissivity greater than silvered Teflon). However, the differences shown approach 25 percent at the higher surface temperatures. Some of the difference may be due to heat loss from the heat pipe saddle to the South Panel which has not been accounted for in the comparison. To adequately assess the test data relative to flight predictions requires that a complete system heat balance analysis be conducted. Since this is beyond the scope of the test data evaluation, only the gross comparison shown in Figure 6-25 has been attempted.

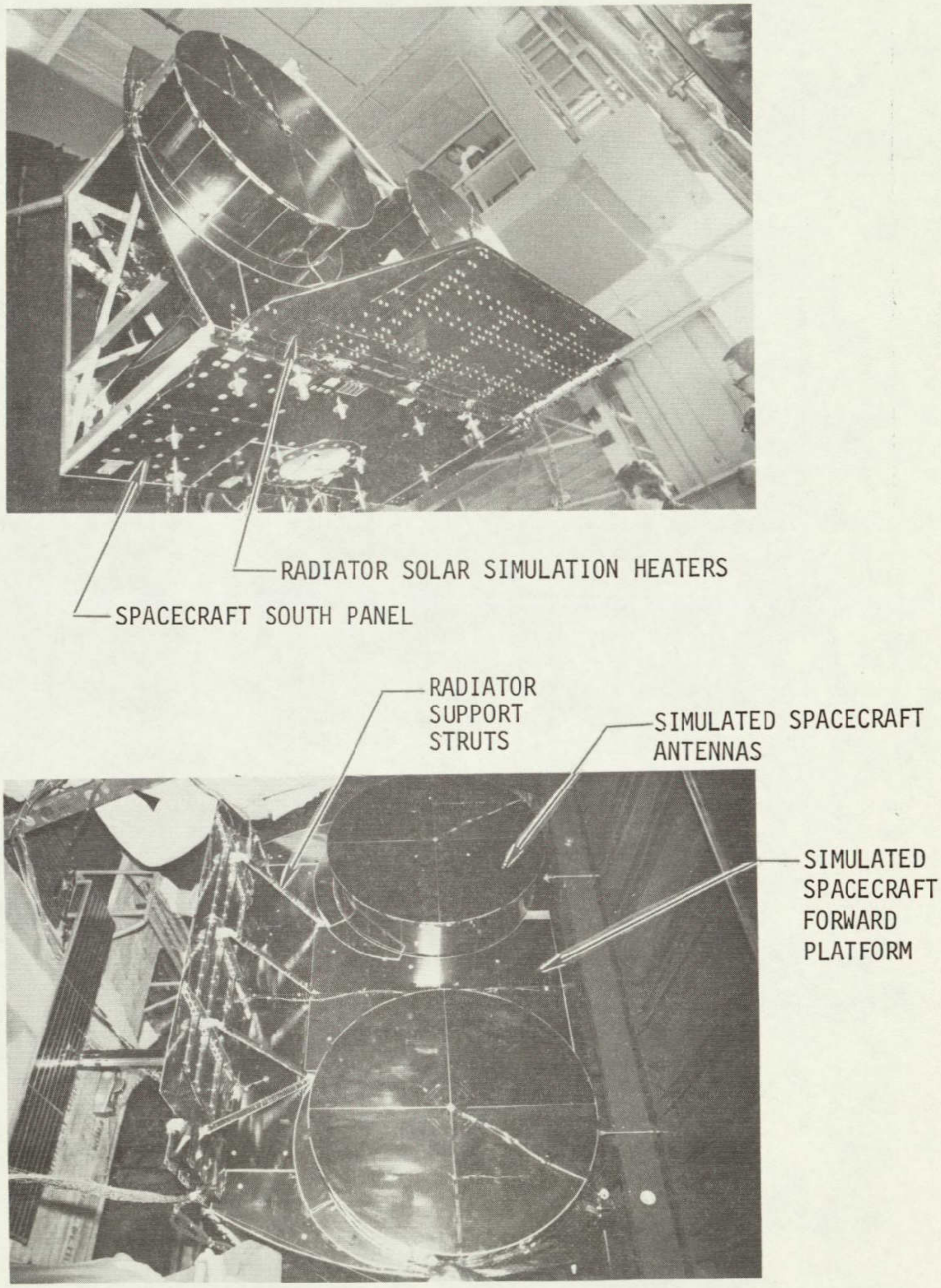


Figure 6-24. VCHPS/South Panel Test Article

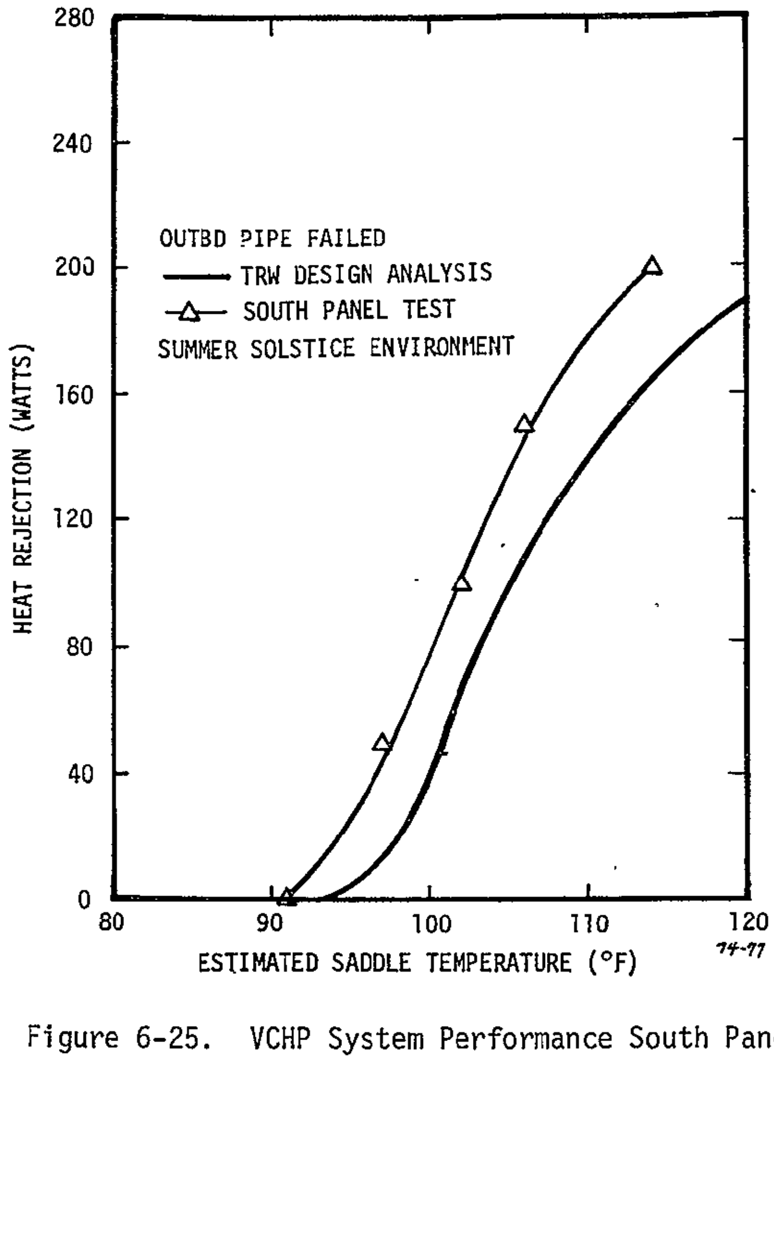


Figure 6-25. VCHP System Performance South Panel Test

The noted comparison does show, however, that the VCHPS has the capability of handling the expected system heat load of approximately 160 watts at a saddle temperature less than 50°C (122°F). In addition the system appears to meet the maximum sink design requirement of 196 watts at a saddle temperature of 50°C (122°F) based on the test data shown in Figure 6-25.

A review of the available South Panel test data was made to assess the heat pipe control range. Of the tests conducted, there was not sufficient thermal load on any of the pipes to turn it full on. Hence, the upper end of the control range (full on temperature) could not be determined. Conversely, with the exception of the -1 heat pipe, data were not obtained at the turn-on points of the heat pipes. The turn-on points of the other two heat pipes (-2 and -3) can only be inferred from the data where the pipes are either on or off. A compilation of on and off points is shown in Table 6-19. Although these data points do not show the turn-on points they do show the heat pipes off when they should be off and on when they should be on.

6.6.2 Minimum Sink Conditions

The minimum sink conditions tests (cases 5 and 8) subjected the heat pipes to subfreezing temperatures in the condenser region for approximately 18 hours. Following this condition the heat pipe arteries appeared to be deprimed. The heat pipe assembly was elevated in heat pipe mode during the test period in question. It is believed that the elevation of the heat pipes contributed to the depriming of the arteries. There are two mechanisms which can cause depriming of the arteries when the condenser is in a frozen state and the heat pipes are elevated. One of the mechanisms is a suction phenomenon due to fluid density changes and the other is vapor diffusion. In order for the arteries of the heat pipe to reprime, the liquid stress at the evaporator end must be lower than the maximum capillary pressure generated by the artery diameter ($4\sigma/D_A$). This is always the case under zero-g conditions when the heat load on the pipe is sufficiently low. However, in 1-g, the stress on the liquid includes a hydrostatic component due to elevation as well as the dynamic component due to load. Priming tests on heat pipes similar to the TEP design indicated that the arteries can prime against a 0.090 inch elevation but not against 0.15 inch. Thus,

Table 6-19. TEP Heat Pipe Control Range Temperatures South Panel Test

HEAT PIPE	HEAT PIPE OFF TEMPERATURE** (°F)	HEAT PIPE ON TEMPERATURE*** (°F)
D315260-1	57	83*
D315260-2	59	99
D315260-3	59	100

*Data obtained at heat pipe turn-off point at end of case 4 test.

**Case 5 equilibrium condition with frozen condenser.

***Case 4 equilibrium.

Reservoir temperatures: -1 = -72°F
-2 = -76°F
-3 = -85°F

with the heat pipes elevated above 0.090 inch after the arteries are primed, the arteries cannot reprime once deprimed without first releveling the assembly. There is, of course, no such constraint in zero-g operation.

Liquid density changes can deprime the arteries by causing the wick structure in the condenser to draw fluid from that in the evaporator. When the heat pipe is elevated as in the NASA/LeRC test, most of the excess fluid resides in the control gas reservoir. With the end of the condenser and gas reservoir frozen the only fluid available to satisfy the wick demand for increased mass as the fluid density changes is that in the fillets, grooves, and excess fluid reservoirs upstream of the freezing point position. Thus, as the solid front (freezing point) progresses toward the evaporator, the fluid density increase ahead of the front due to the temperature drop causes the wick to draw fluid from the fillets and grooves upstream. As the fillets decrease in size the stress in the evaporator increases until it reaches the critical stress of the arteries. When this point is reached any further suction will deprime the arteries.

While this process takes place regardless of whether the heat pipe is elevated, level, or in a zero-g field, there is a significant difference in excess fluid availability in the latter two instances. For level or zero-g conditions the heat pipes' excess fluid reservoirs in the evaporator are filled with fluid at low enough loads to result in freezing. On the other hand, when tilted above 0.230 inch in a 1-g field these reservoirs empty part way up the condenser due to the hydrostatic head. This difference in evaporator fluid inventory at the beginning of the freezing process appears sufficient to account for artery depriming in the 1-g case and assure no depriming in the 1-g level or zero-g cases.

The second mechanism contributing to artery depriming is "diffusion freezeout". During the sub-freezing conditions in the condenser, vapor diffuses from the evaporation region of the heat pipe to the location of sub-freezing temperatures. As with the fluid suction mechanism, diffusion freezeout depletes the fluid in the evaporator until the artery critical stress is reached and the artery deprimes. Analysis shows, however, that under the conditions of the TEP application, diffusion freezeout is much less effective in depleting evaporator fluid mass than is the suction mechanism described above.

To rigorously analyze the fluid suction effect due to freezing is a difficult task since, once the end of the condenser and gas reservoir are frozen, the stress upstream of the freezing front and the volume of fluid per unit length continuously change with time as freezing progresses. Rather than write the digital computer program necessary for rigorous solution, upper and lower bound calculations were performed using existing analytical tools which conservatively predict whether or not the arteries will deprime.

To obtain an upper bound for the mass redistribution due to suction, it was assumed that the entire system is at 70°F when the heat pipes first shut off (the predicted shut-off temperature for minimum sink conditions).* The MULTIWICK computer program (Reference 6) was then used to obtain the pre-freezing mass distributions for zero-g (1-g level is similar) and 1-g shut-off conditions for the -1 heat pipe. These are shown as the solid lines on Figures 6-26 and 6-27 respectively. In Figure 6-27 for the 1-g tilted case, the upper bound condition relates to the m' initial-max curve which assumes the excess fluid reservoirs are full up to the 1/4 inch elevation point. The lower bound case is shown as the m' initial-min curve which assumes the excess fluid reservoirs are empty. The MULTIWICK program predicts that these reservoirs are marginally full under these conditions but the program is not very accurate as regards this calculation and small

*This assumption underestimates the mass per unit length -m' in the condenser which would normally be colder than the evaporator at the shut-off point.

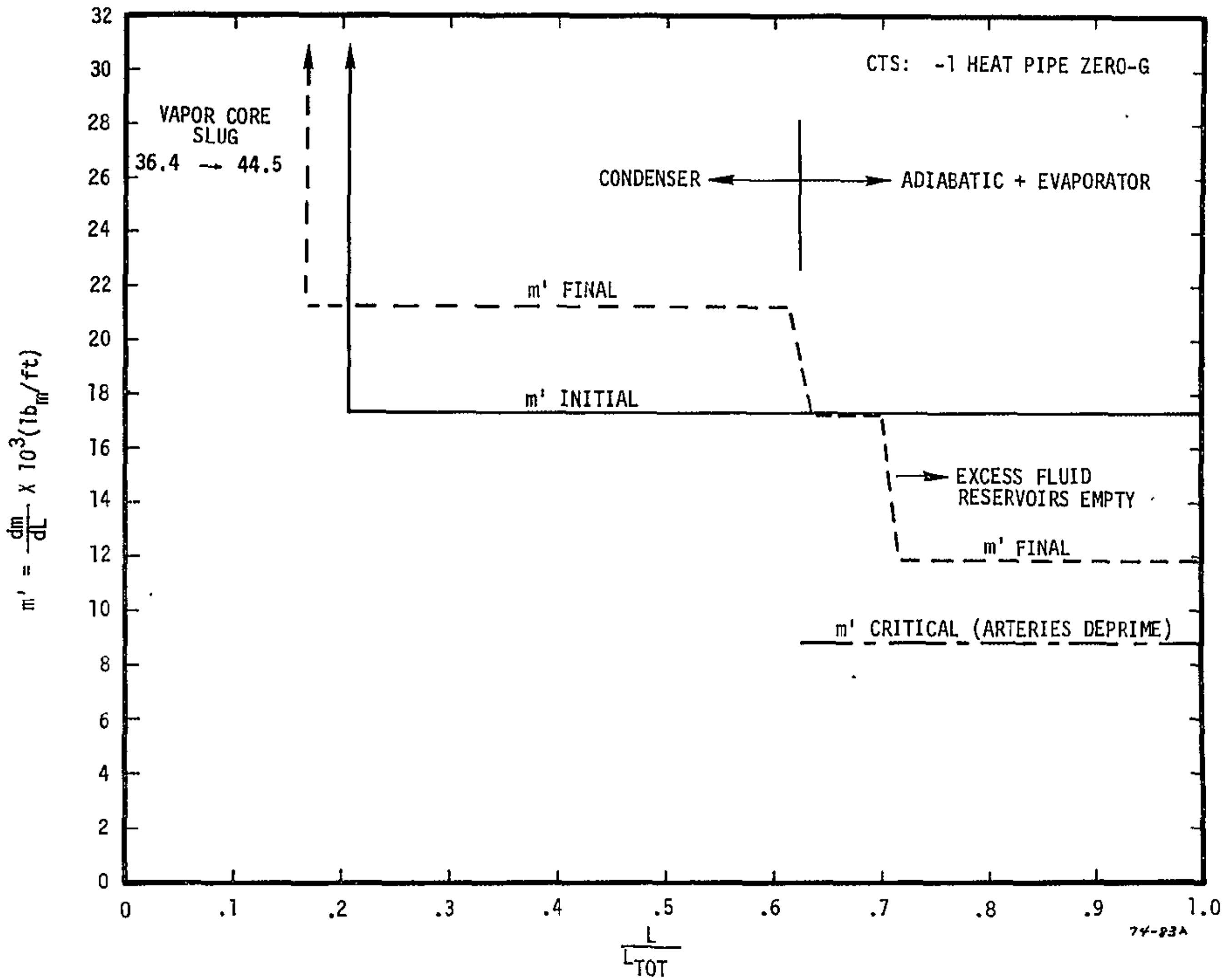


Figure 6-26. Mass Redistribution Due to Condenser Freezing in Zero-g

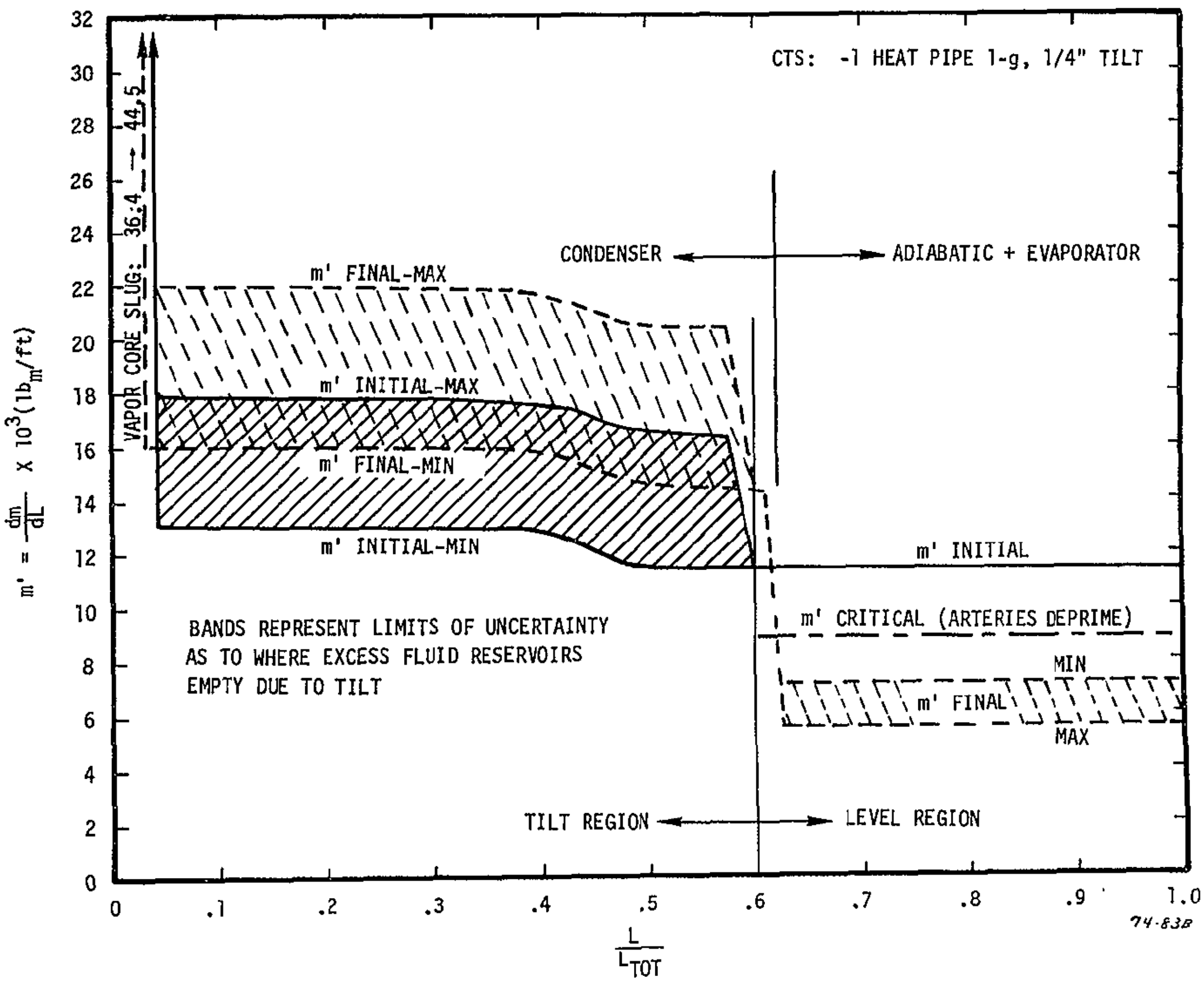


Figure 6-27. Mass Redistribution Due to Condenser Freezing in One-g with 1/4 in Tilt

variations in elevation or internal wick geometry can have a significant influence on the point at which the reservoirs empty. Priming tests on similar heat pipes suggest the reservoirs may only be full to an elevation of less than 0.15 inch. The shaded region between the solid lines represents the probable maximum band of uncertainty in pre-freezing mass distribution.

After the gas reservoir and the end of the condenser freeze, all excess fluid in these regions is bound up in solid form. Thus, as the freezing front progresses upstream and the local density increases, the fluid necessary to maintain a constant volume distribution in the condenser must be drawn from the evaporator and adiabatic section.* This results in a reduction in mass per unit length within the adiabatic and evaporator sections which, if sufficient, causes the arteries to deprime.

The increase in mass per unit length due to freezing from 70°F at constant volume is given by:

$$\Delta m' = \left(\frac{\rho_{solid}}{\rho_{70°F}} - 1 \right) m'_{initial} \tag{1}$$

where:

m' - mass per unit length

ρ_{solid} - density of solid methanol at the freezing point

$\rho_{70°F}$ - density of liquid methanol at 70°F.

Thus, the total mass increase in the condenser due to freezing is:

$$\Delta m = \left(\frac{\rho_{solid}}{\rho_{70°F}} - 1 \right) \int_{\substack{\text{Vapor} \\ \text{Core} \\ \text{Slug}}}^{L_c} m' dL \tag{2}$$

*The constant volume assumption overestimates the suction demand. The volume per unit length at the freezing front continuously diminishes as the stress in the unfrozen portion of the pipe increases due to fluid depletion.

This mass is drawn from the adiabatic and evaporator sections resulting in a reduction of m' ($\rho_{70°F}$ X Δ volume) in these regions such that:

$$-\Delta m = \int_{L_c}^{L_{tot}} (m'_{final} - m'_{initial})dL \qquad (3)$$

The result of this mass depletion differs in the zero-g and 1-g, 1/4 inch tilt cases. In the zero-g case, Figure 6-26 shows that it results in partial emptying of the initially full excess fluid reservoirs within the evaporator such that the final mass inventory is still in excess of the critical m' which would cause artery depriming. This value - $m'_{critical}$ - was obtained from the MULTIWICK program as that mass per unit length corresponding to the critical artery stress at 70°F. Numerically, the mass transferred from the adiabatic and evaporator sections to the frozen condenser is estimated at 0.0093 lb_m. This available mass (that which would cause incipient artery depriming) is given by:

$$\int_{L_c}^{L_{tot}} (m'_{initial} - m'_{critical})dL \qquad (4)$$

and equals 0.0185 lb_m. Thus, the available mass exceeds that required by a factor of two using a very conservative argument, suggesting that the arteries would not deprime by this mechanism in a zero-g environment. A similar argument holds for the 1-g level case.

In the 1-g tilted case, Figure 6-27 shows that the mass redistribution due to freezing should deprime the arteries. Depending on whether the upper or lower bound initial condenser mass distribution is assumed, the mass transferred to the condenser is approximately 0.0126 lb_m or 0.0093 lb_m, respectively. Since the excess fluid reservoirs in the adiabatic and evaporator sections were empty to begin with, the mass reduction in this region results in a depletion from the remaining wick elements yielding final values of m' equal to 0.0056 lb_m/ft and 0.0071 lb_m/ft for the upper and lower bound initial condenser inventories respectively. This compares with m' for artery depriming of 0.00883 lb_m/ft. Corresponding to this, the available mass Equation (4) equals 0.0056 lb_m, which in this case is approximately half that required by freezing. This is consistent with the observed failure in the NASA/LeRC tests.

The second mechanism which can cause arterial depriming is diffusion freezeout. The diffusion freezeout rate is given by:

$$\dot{m} = -cA_v M \mathscr{D} \left.\frac{dx}{dT}\right|_{T = T_F} \cdot \left.\frac{dT}{dL}\right|_{L = L_F} \qquad (5)$$

where:
- $\dot{m}$ - mass transfer rate
- c - molar density
- M - molecular weight of methanol
- $\mathscr{D}$ - diffusivity of vapor-gas pair
- x - mole fraction
- T - Temperature
- T_F - Freezing point
- L - Axial coordinate
- L_F - Axial position of freezing point

Using the NASA/LeRC equilibrium test condition during the frozen period to obtain dT/dL, Equation (5) yields a diffusion freezeout rate of 2.54×10^{-8} lb_m/hour. This is negligibly small rate compared with the mass transferred by suction as described above. It would require 400,000 hours to transport the 0.01 lb_m shown to be involved in the suction process.

The conclusions which can be drawn from the previous discussion are as follows:

1) The probable cause of artery depriming observed in the NASA/LeRC test of SN001 was depletion of fluid from the evaporator by suction to the condenser due to the fluid density increase in the condenser as it cooled and froze. Because the system was tilted the mass available in the adiabatic and evaporator sections was insufficient to satisfy the suction requirement without increasing the liquid stress beyond that which deprimes the arteries.

2) When operated in a zero-g environment, or level in a 1-g environment, the mass of liquid in the evaporator region is more than sufficient to meet the redistribution requirements and the arteries should not deprime.

3) Although the diffusion freezeout phenomenon also acts to transfer mass from the evaporator to the condenser under frozen conditions, the rates in the TEP application are insignificant compared with the mechanism described above.

4) In the event of artery failure due to one of the above mechanisms, the arteries can reprime when the condenser thaws in a zero-g or 1-g level condition before a heat load is applied. However, they cannot reprime in a 1-g, elevated configuration which resulted in the heat pipe failure observed in the T/V test.

6.7 VCHPS VIBRATION TEST

The VCHPS structural design was qualified by a vibration test on the SN001 assembly conducted by NASA/LeRC personnel. The VCHPS was mounted to a shake table as shown in Figure 6-28. The struts are attached to a spacecraft Forward Platform simulator panel which is rigidly attached to the shake table.

As of the writing of this report the VCHPS vibration test results report had not been issued by NASA/LeRC. The preliminary evaluation of the test results indicates that the structural design of the VCHPS meets all design requirements.

6.8 SILVERED TEFLON TESTS

The silvered Teflon was tested both at TRW and at NASA/LeRC for adherence to substrates under low temperature thermal cycling. The silvered Teflon was applied to a test panel and was cycled 1265 times between 32°C (90°F) and -90°C (-130°F) and 1300 times between -18°C (0°F) and -129°C (-200°F). The panel tests were conducted at TRW and were reported in Appendix C of Reference 3. For the details of the test the reader is referred to the noted reference.

Two test coupons were tested at NASA/LeRC by cycling between -18°C (0°F) and -157°C (-250°F). The first test coupon was the panel tested previously at TRW and the second coupon was a segment of heat pipe and condenser saddle coated with silvered Teflon. While the test report has not yet been issued, preliminary indications are that the silvered Teflon applications successfully passed both tests.

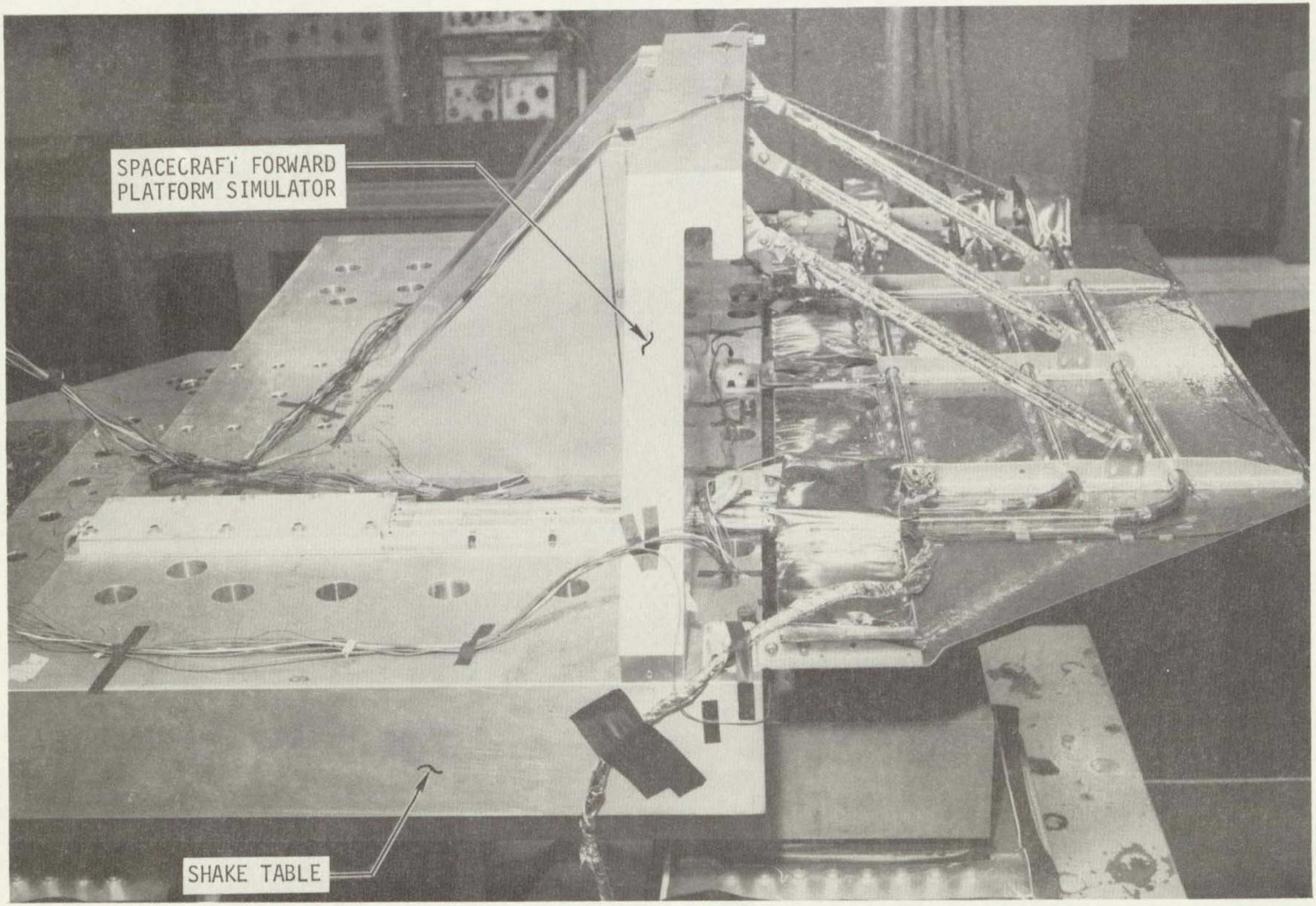


Figure 6-28. VCHPS Vibration Test Configuration

REFERENCES

1. Interface Control Document, Variable Conductance Heat Pipe/Radiator, Transmitter Experiment Package, 4761-TEPN-248 (Rev. A), dated 11 September 1973.

2. TRW Document 4761-TEPN-367, TEP Variable Conductance Heat Pipe System Critical Design Review Package, dated 25 April 1974.

3. NASA/LeRC Letter No. 3301, Approval of Heat Pipe Critical Design Review, dated 21 May 1974.

4. TRW Document 4761-TEPN-283, TEP Variable Conductance Heat Pipe System, Preliminary Design Review Package, dated 11 September 1973.

5. TRW Document 4761-TEPN-296, TEP VCHPS/Radiator System Thermal Analysis Model, dated 3 October 1973.

6. TRW Report 20509-6027-RU-00, User's Manual for the TRW MULTIWICK Program, dated June 1974.